600/7-80-103

United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Cincinnati OH 45268

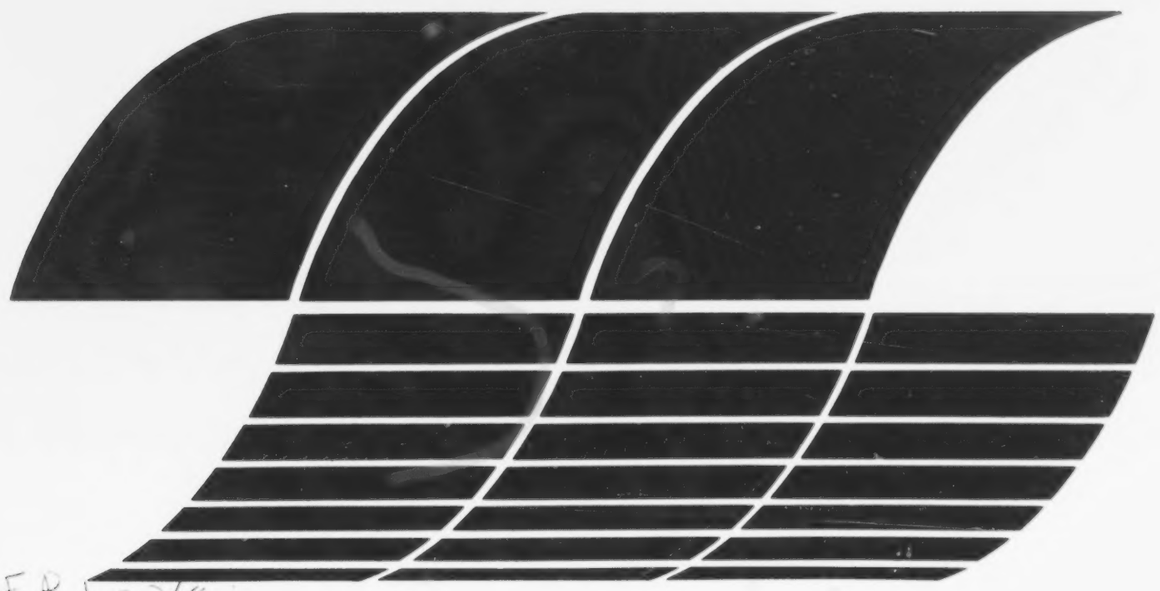
EPA-600/7-80-103
May 1980

Research and Development

EPA

Wood Waste as a Power Plant Fuel in the Ozarks

Interagency Energy/Environment R&D Program Report



FP 1.23/8:

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the INTERAGENCY ENERGY-ENVIRONMENT RESEARCH AND DEVELOPMENT series. Reports in this series result from the effort funded under the 17-agency Federal Energy/Environment Research and Development Program. These studies relate to EPA's mission to protect the public health and welfare from adverse effects of pollutants associated with energy systems. The goal of the Program is to assure the rapid development of domestic energy supplies in an environmentally-compatible manner by providing the necessary environmental data and control technology. Investigations include analyses of the transport of energy-related pollutants and their health and ecological effects; assessments of, and development of, control technologies for energy systems; and integrated assessments of a wide range of energy-related environmental issues.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

EPA-600/7-80-103
May 1980

WOOD WASTE AS A POWER PLANT FUEL IN THE OZARKS

by

V. J. Flanigan
Mechanical Engineering Department
University of Missouri - Rolla
Rolla, Missouri 65401

Grant No. R804270-010

Project Officer

Harry Freeman
Incineration Research Branch
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Industrial Environmental Research Laboratory-Cincinnati, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

best copy available

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

In an attempt to solve the problem of wood waste disposal, the study described here was initiated to study the possibility of using the waste as a supplement to present coal fire facilities. The overall goal was to promote the economic and energy conservation and pollution free characteristics of this material. This report will be of interest to those considering supplementary coal with wood chips. Requests for further information should be addressed to the Incineration Research Branch, IERL-Cincinnati.

David G. Stephan
Director
Industrial Environmental Research Laboatory
Cincinnati

ABSTRACT

The report discusses the testing program conducted on a chain-grate stoker boiler with a blended coal and wood waste fuel. The boiler was designed to produce 18,000 lb/hr (8,200 kg/hr) of saturated steam at 150 psig (103.4 N/cm^2). The objective of the tests was to determine the difference, if any, in the performance and the emissions of the boiler co-firing wood and coal as compared to firing coal alone. Four different coals with different sulfur contents were fired with the wood waste. The wood waste content was varied up to 2/3 by volume.

Particulate loadings, opacity and concentrations of sulfur dioxide, nitrogen oxide and total hydrocarbons in the flue gas were measured. Also, cyanide concentrations and particulate polycyclic organic emissions were determined for some of the runs. The baseline for all data comparisons was obtained by running the boiler with a particular pure coal.

The boiler performance was reported by plotting the boiler efficiency as a function of the wood percentage in the fuel and by plotting a performance index defined to be the pound of steam produced per pound of fuel fired versus weight percent wood. The efficiency curve showed a slight increase with increasing wood content while the performance index naturally decreased due to the lower heating value of the wood. The performance index was used to predict the operational savings from supplementing the coal with the wood waste.

Results indicate that particulate and nitrogen oxide emissions are not substantially altered by using wood waste as supplemental fuel with coal for the test conditions adopted in the program. Sulfur dioxide emissions decreased with increased proportions of wood waste in the coal-wood mixture, whereas total hydrocarbon concentration increased when wood waste content was increased. Cyanide concentrations were not substantially affected by substitution of wood waste for coal; particulate polycyclic organic emissions were below the detectable limits for all fuels used in the tests.

CONTENTS

Foreword iii
Abstract iv
Figures vi
Tables viii
Abbreviations and Symbols ix
Acknowledgment xi

1. Introduction 1
2. Conclusions 3
3. Recommendations 5
4. Materials and Methods 6
   - Fuel Characteristics 6
   - Fuel Availability 8
   - Fuel Handling 13
   - Fuel Firing 15
5. Experimental Procedures 22
   - Fuel Test (MRI) 22
   - Sampling and Analysis Methods 24
6. Results and Discussion 26
7. Experimental Procedures 46
   - Fuel Testing (UMR) 46
   - Analysis 48
8. Results and Discussion 52

References 67
Appendices

A. Facilities Statement 69
B. Data Collected and Calculated 70
C. Report of Analysis 73

FIGURES

Number		Page
1	U.S. Forest Service Regions for Missouri	9
2	Fuel Handling Diagram	14
3	Boiler Sketch	16
4	Boiler Modifications	19
5	Fuel Supply Sketch	20
6	Power Plant Breeching System	23
7	Section of the Sampling Location	25
8	Particulate Loading as a Function of the Excess Air	43
9	Particulate Correction as a Function of Weight Percent Coal	44
10	Sulfur Dioxide Emissions as a Function of Fuel Blend and Coal Sulfur Content	53
11	Normalized Sulfur Dioxide Output as a Function of Wood Percent	54
12	Nitrogen Oxides Emissions as a Function of Fuel Blend	55
13	Opacity of Flue Gas as a Function of Excess Air and Coal Sulfur Content	56
14	Opacity as a Function of the Weight Percent of the Coal	57
15	Opacity Correction Curve as a Function of the Weight Percent Coal	59
16	Dry Gas and Unburned Combustible Losses as a Function of Fuel Blend	60

Number Page

17 Moisture Losses Due to Fuel Hydrogen, Air Moisture, and Fuel Moisture as a Function of Fuel Blend 61

18 Net Efficiency Excluding Radiation and Unaccounted Losses as a Function of Fuel Blend 62

19 Performance Factor (Pound Steam per Pound Fuel) as a Function of Fuel Blend 63

20 Economic Results from the Blended Fuel Use 66

TABLES

Number		Page
1	Percentage of Sulfur Contents on the Dry Basis	6
2	Fuel Ultimate Analysis (% by weight) and Heating Values (Dry Basis)	7
3	Residue Production Pounds per Year	8
4	Missouri Forest Products Industries Near Rolla, MO	11
5	Test Results (Uncorrected)	29
6	Test Results (Corrected)	35
7	Comparison of Measured and Calculated Flue Gas Flow Rates	41
8	Comparison of 1974 Compliance Test with Coal-Only Results of Current Programs	45
B-1	Test Data	70
B-2	Test Data Plotted	71

ABBREVIATIONS AND SYMBOLS

SYMBOLS

A -- Weight percentage of ash in the net fuel fired

C -- Weight percentage of carbon in the net fuel fired

C_{AB} -- Weight percentage of carbon actually burned in the net fuel fired

FR -- Fuel firing rate

G -- Volume ratio of wood to coal in the blended fuel

H_2 -- Weight percentage of hydrogen in net fuel fired

H_c -- Weight percentage of hydrogen in coal

H_w -- Weight percentage of hydrogen in wood

HHV_c -- Dry higher heating value of coal

HHV_f -- Dry higher heating value of net fuel

HHV_w -- Dry higher heating value of wood

L_A -- Loss due to moisture in air

L_{DG} -- Loss due to dry flue gases

L_H -- Loss due to hydrogen in fuel

L_m -- Loss due to moisture in fuel

L_R -- Loss due to unburned combustible in refuse

M_c -- Weight of coal added along sides of stoker

M_F -- Weight of blended fuel fired

MC_c -- Moisture content of coal

MC_w -- Moisture content of wood

MW -- Molecular weight of flue gas

N_2 -- Weight percentage of nitrogen in net fuel fired

O_2 -- Weight percentage of oxygen in net fuel fired

O_c -- Weight percentage of oxygen in coal

O_w -- Weight percentage of oxygen in wood

P -- Pressure

R -- Ideal gas constant

S -- Weight percentage of sulfur in net fuel fired

S_{AB} -- Weight percentage of sulfur actually burned in net fuel fired

T -- Temperature

T_A -- Air temperature

T_G -- Flue gas temperature

V_{ACT} -- Actual volume of dry flue gas per 100 pounds of fuel

V_{AIR} -- Actual volume of air entering boiler per pound of fuel

V_{CT} -- Theoretical dry flue gas volume per 100 pounds of fuel

V_{EA} -- Average volume of excess air per 100 pounds of fuel

$V_{EA}|_{CO_2}$ -- Volume of excess air per 100 pounds of fuel from carbon dioxide analysis

$V_{EA}|_{O_2}$ -- Volume of excess air per 100 pounds of fuel from oxygen analysis

V_{TN} -- Volume of nitrogen in theoretical air per 100 pounds of fuel

V_{TO} -- Volume of oxygen in theoretical air per 100 pounds of fuel

W_{DG} -- Weight of dry gas per pound of fuel

W_H -- Weight of moisture per pound of fuel

W_m -- Weight of air moisture per pound of fuel

WF_c -- Weight fraction of coal in blend

x -- Weight ratio of wood/weight of fuel

y -- Weight ratio of coal/weight of the fuel

Z -- Weight percentage of a constituent (excluding oxygen, hydrogen) of net fuel fired

Z_c -- Dry weight percentage of a constituent (excluding oxygen, hydrogen) of coal

Z_w -- Dry weight percentage of a constituent (excluding oxygen, hydrogen) of wood

$\%CO_2$ -- Volumetric percentage of carbon dioxide from Orsat

$\%O_2$ -- Volumetric percentage of oxygen from Orsat

β -- Weight fraction of carbon in the refuse

γ -- Weight fraction of sulfur in the refuse

ρ -- Density of the constituent

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the Environmental Protection Agency for the financial support of this project and to Mr. Harry Freeman for his help and guidance during the tenure of the project.

The author also would like to thank the Chancellor for his encouragement and confidence in the work undertaken. A special thanks also goes to the power plant operating and maintenance personnel who were always helping and to Elmer Doty, the graduate student who assisted in obtaining the data.

The author also thanks Art Spratlin and Jim Kelly of the EPA regional office in Kansas City for the loan of the Method 6 sampling equipment, which greatly helped in the testing.

INTRODUCTION

The report defines the experience at the University of Missouri-Rolla with a boiler fuel, which consisted of a blend of wood residue and coal. This study was undertaken to save an unrenewable resource, coal, and at the same time conserve energy by using a waste product.

The conversion of waste products to energy has become an attractive and necessary means of disposing of waste material. The success of this expedient was attested to by the programs at Union Electric in St. Louis, Mo. (1), and the program in Ames, Iowa (2). The facilities both burned solid waste derived fuel to produce electricity. The wood industry in the Northern States of the U.S. has long used waste wood as an energy source.

The wood industry in the state of Missouri is represented by approximately 500 sawmills, most of which are too small to use their waste as an energy source, but the waste represents a huge amount of material and a severe problem. The problems arise from the danger of fires in the stockpiles, difficulties with run-off and simply the large amount of land required. Previously, the waste was simply stockpiled or burnt in a teepee burner, but neither of these options are presently satisfactory, leaving the operator with the thoughts of land-filling the material. The land-fill solution becomes especially critical when one examines how depressed the industry has been and how important it is to the states' economy.

With these facts one immediately begins to consider the energy content of the waste and its value as a fuel.

The University of Missouri-Rolla is located at the edge of the Eastern Ozark Region, the most heavily forested area of the state. At this location, the University has been investigating the possibility of using wood waste to fuel their central power plant, which provides the heating and cooling load for the campus.

The estimated coal need at the plant for FY 1977-78 was 12,000 tons at an estimated cost of approximately $450,000. A savings here would be of great benefit to the University and the people of the state. The coal normally used in the plant is an Illinois blend of high and low sulfur coal providing a maximum sulfur content of 2%; the wood was a hardwood blend mostly oak

with zero sulfur content.

The primary objective of this report is to present and discuss experimental results obtained from the monitoring of the flue gases and the performance characteristics of a boiler fired with blends of coal and hardwood waste (primarily oak chips). The research was performed using a boiler located in the University of Missouri-Rolla Power Plant from January through August 1977.

Results are presented for sulfur dioxide emissions, nitrogen oxides and particulate effluents. The gaseous pollutants, presented as weight per unit energy input, are treated as a function of both the sulfur content of the coal and the weight percentage of wood in the fired fuel. Particulate effluents are presented as opacity and particulate versus percent excess air and weight percent coal.

The report also discusses potential hazardous organic materials that may be omitted with the use of wood waste.

The boiler performance was addressed in terms of the boiler heat balances for the different blends of each of the coals. The overall efficiency of the unit was obtained from this data for each run providing the data necessary to suggest a yearly cost with that particular fuel blend. The blended fuel costs were compared to the all coal operating cost and the dollar savings presented.

CONCLUSIONS

In this investigation, the relative performance of coal and coal/wood blends as fuel was investigated experimentally. The conclusions arising from this work are as follows:

1. Wood waste burned in conjunction with coal exhibits heat losses that vary as predicted, and result in relative efficiencies somewhat higher than pure coal. Simply stated, the utilization of the heat released per unit weight of fuel is slightly improved.

2. The performance factor tended to decrease slightly with the addition of wood to the blended fuel. Whether or not this decrease is significant depends on the size of the plant and the extenuating economic factors. For this particular unit, the use of a composite coal/wood fuel appears as an attractive proposition. In fact, savings of up to $35,000/year were suggested with large decreases in the coal used.

3. The boiler response is affected by the blended fuel. The boiler cannot respond to a change in load in the same sense as when firing all coal. The blended fuel requires more attention and skill from the fireman.

In this report, the emission characteristics of various blends of coal and hardwood waste were also investigated experimentally in conjunction with the boiler performance. The conclusions arising from this work may be stated as follows:

1. Sulfur dioxide emissions expressed unit weight per unit heat input were shown to be measurable with a relatively high degree of accuracy. Emissions decreased as expected when the wood content of the blend was increased. In fact, the sulfur dioxide emissions may be satisfactorily approximated from the sulfur content and the heating value of the coal.

2. Emissions of nitrogen oxides were not visibly dependent on the wood to coal ratio of the fired fuel. However, the lack of flame temperature data does not permit complete resolution of these effects.

3. The examinations of the particulate emissions and opacity data for the different fuels, with the corrections for excess air, point out that the particulate wasn't substantially altered by the use of the wood waste. This conclusion was based on the zero slope of the corrected opacity data and the slight decrease in the particulate data with increased coal content. The opposite slope of the opacity data (uncorrected) as compared to the particulate data also leads to this conclusion.

4. Total hydrocarbon concentrations increase with increased substitution of wood waste for coal. For coal-only tests, hydrocarbon emissions averaged 4.25 ppm, and for one volume wood waste plus one volume coal, hydrocarbon levels were 6.2 ppm. When two volumes wood waste were used with one volume coal, the average hydrocarbon emissions were 8 ppm.

5. Cyanide concentration was not substantially affected by substitution of up to approximately 50% of coal with wood waste.

6. Particulate Polycyclic organic emissions were below detectable limits for all fuels used.

RECOMMENDATIONS

It is recommended that from the results of this study the University consider firing one of the two small boilers on a blended fuel. It is recommended that the firing be on the continuous basis and for a period of one year.

In order to reduce the difficulties experienced with ignition problems, high stoker speeds, high gate settings, and slow response the University should consider a higher energy blend. A blend of 20% by weight wood, 39% by volume, would be a possibility. The blend suggested would still provide a 12% savings in fuel cost and would provide the higher Btu content per pound of fuel.

The demonstration of an extended operation on blended fuel at some reasonable boiler load would provide valuable operating data, including the demonstration of any slagging and ash problems, if they exist. The demonstration would also provide emphasis to encourage other users to study the possibilities of adapting wood waste to their combustion system.

FUEL CHARACTERISTICS

The fuel used consisted of either a pure coal or a blend of wood and coal, a requirement of boilers equipped with chain-grate stokers. The operating instructions of these stokers state a requirement of a minimum of a 6 to 7% ash content in the fuel used. The ash content of the wood chips was less than 1%, and required that the chips were always blended with the higher ash coal. This ash requirement provides protection for the moving chain from the radiant energy of the fire.

The stoker's manufacturer also recommended these stokers for a wide range of screened bituminous coals, suggesting a maximum 1 inch top size and a minimum of 28 mesh for fines. The coal normally used at the plant is a blended Illinois coal normally providing a 2% sulfur content on the as received basis. A sample screen test and proximate analysis of the blended coal is given in Appendix C. This analysis meets the coal specifications suggested by the manufacturer.

The coal used in the test program was as follows; the normal blended Illinois coal, Ziegler coal, Orient coal, and River King coal. The blended coal normally used was a blend of 60% Orient and 40% Ziegler. The sulfur content of these fuels is given in Table 1. The ultimate analysis for these coals and the wood, as measured by an industrial laboratory, is given in Table 2.

TABLE 1. PERCENT SULFUR CONTENTS ON THE DRY BASIS

Orient	Ziegler	Blended (Orient & Ziegler)	River King
1.91	3.12	2.44	3.29

The wood used for the most part was hardwood chips. The chips on an average were 1 inch square by 1/8 inch thick (6.54 cm^7 x 0.3174 cm). They were produced by chipping debarked slabs of mixed hardwoods. The sulfur content of course was very low, typically zero, though the laboratory analysis reported some trace of sulfur in the wood fuel. Other fuels used on a limited basis were sawdust and bark. The bark was the result of the debarking of the hardwood logs and contained a large percentage of wood fiber. The bark's size distribution was

TABLE 2. FUEL ULTIMATE ANALYSIS (% BY WEIGHT) AND HEATING VALUES (DRY BASIS)

	Blended Coal No. 1	Ziegler Coal No. 2	Orient Coal No. 3	River King Coal No. 4	Wood
Carbon	72.515	69.114	71.955	67.67	50.18
Hydrogen	4.957	5.227	5.104	4.4	5.06
Oxygen	8.560	6.997	9.706	11.04	43.00
Nitrogen	1.585	1.176	1.477	1.02	0.30
Sulfur	2.444	3.120	1.911	3.29	0.15
Ash	9.939	14.366	9.847	11.98	1.31
Higher Heating Value					
Btu/lb	11,830	12,560	12,680	12,633	8,770
MJ/KG	27.5	29.2	29.5	29.4	20.4

typically a mixture varying from long fibers of approximately 3 inches (7.62 cm) to a considerable concentration of fines. The sawdust was all fines and the dust was collected off the header saw in the mill.

FUEL AVAILABILITY

Looking at the Missouri Sawmills, it is of interest to note that approximately 50% of the incoming log ends up as sawdust, edgings or possibly bark or chips, depending on the mill. The waste percentage was taken from the work accomplished by the Missouri Conservation Department for Missouri Sawmills (3). Of course the actual percent of waste was dependent on the size of the logs, material to be produced, and the actual mill operation. To give an indication of the availability of wood waste a survey of existing stock piles and annual production of wood waste in the Eastern Ozark Region of the State was taken (4).

The Eastern Ozark Region, shown in Figure 1, is the most heavily forested area of Missouri. The figure was taken from the NCFES bulletin, U. S. Forest Service, USDA, 1972 (5). The percentage of forested area is given below the name of each region in Figure 1.

This Eastern Ozark Region is naturally the area representing the most active forest industry in the state. The survey not only looked at the residue from the mills, but also from manufacturing operations like pallet plants, flooring mills, etc. The annual production for this region was 1,764,563,000 pounds of residue, broken up as in Table 3.

TABLE 3. ANNUAL RESIDUE PRODUCTION
EASTERN OZARK REGION (pounds)

Sawdust	571,800,000
Trim	82,210,000
Shavings	70,200,000
Slabs/Edgings	882,080,000
Bark	154,400,000
Shreds	3,860,000
Total	1,764,550,000

This represents an annual production of $10,587,300 \times 10^6$ Btu, based on a Btu content of 6,000 Btu/lb, and amount to 880,000 tons. At the same time, in just this region, there are 2,317,880,000 pounds (1,150,000 tons) of residue existing in

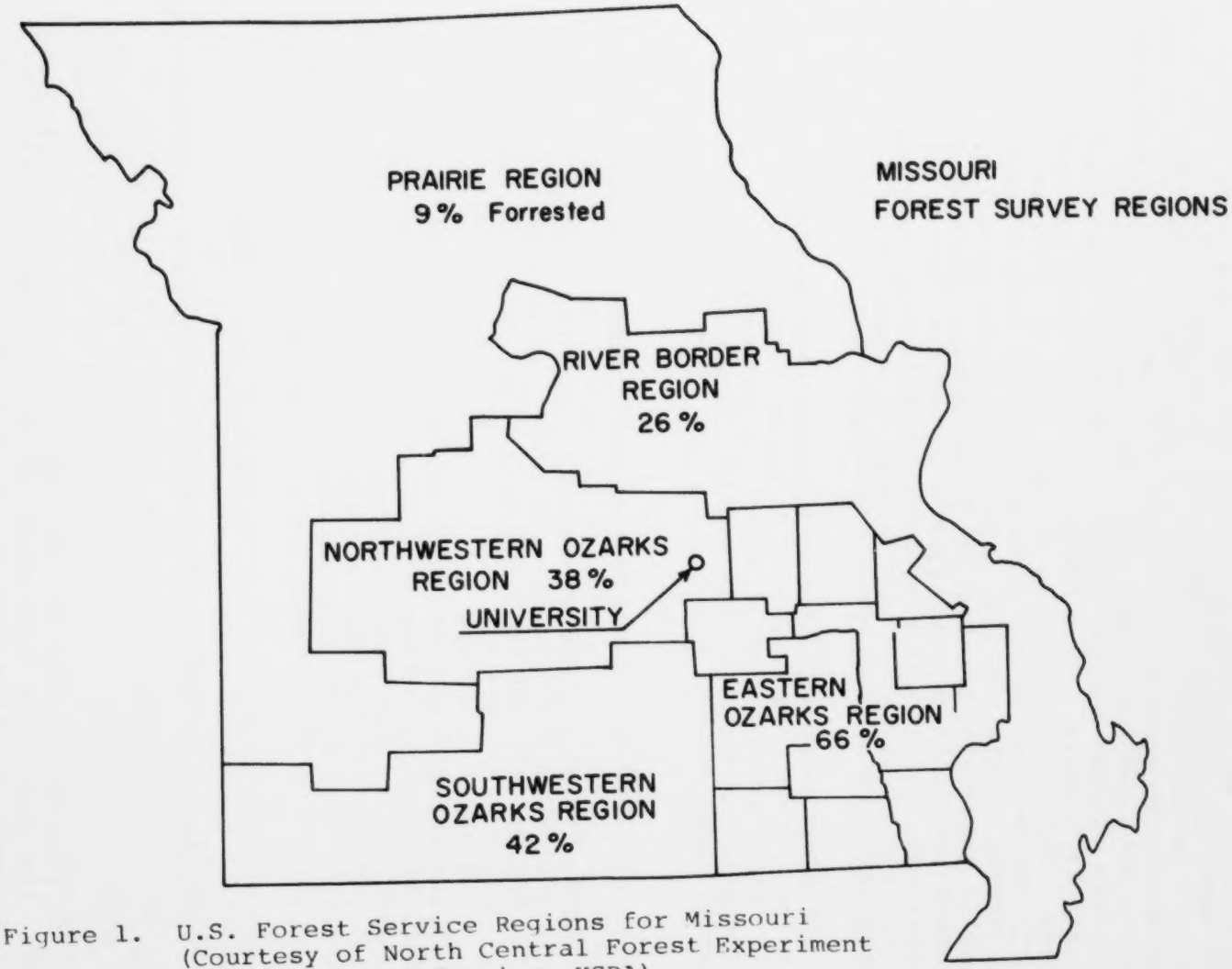


Figure 1. U.S. Forest Service Regions for Missouri (Courtesy of North Central Forest Experiment Station, Forest Service, USDA)

dumps and stockpiles. The Residue specialist for the Conservation Commission approximated that another 1,500,000 tons are produced annually in the other regions of the state. The total quantity of waste comes to some 2,400,000 tons. The tonnage does not consider residue in the woods in so far as 50% of the tree is left in the woods as slash. A portable chipper and skidder could quickly convert the slash to chips and at the same time remove poor quality timber for stand improvements (6). The portable chipper system could provide even larger quantities of available Biomass. Even though the developers and users of these total tree harvesting systems need to exercise care in their use because of the problems and the lack of understanding in regards to the nutrient removal (7) from the soils. This care is especially critical in clear cutting operations. The Biomass was definitely available in residue form for this experiment, but it was also apparent that much more was available in the way of slash and cull timber if a need could be established.

Further documentation of the available wood waste in this area can be derived from wood industry data. The first consideration might be the sawmill sizes and production. In 1975 the Missouri Department of Conservation published the following sawmill distribution (8);

Production per year	Number of Sawmills
Under 100 Million Board Feet	152
100 MBF - 249 MBF	99
250 MBF - 499 MBF	77
500 MBF - 749 MBF	41
750 MBF - 999 MBF	24
1,000 MBF - 1,999 MBF	68
2,000 MBF - 2,999 MBF	33
3,000 MBF - 3,999 MBF	10
4,000 MBF - 4,999 MBF	5
5,000 MBF - 7,499 MBF	3
7,500 MBF - and greater	3
	517

University of Missouri-Rolla's location as a potential user was also established through the following mileage table (9) (Table 4). The table shows the concentration and activity of the wood industry in the area surrounding the University.

In this work, only the available fuel at the sawmills was used. The wood chips were obtained from the Reed Lumber Co., approximately 60 miles from Rolla. They were delivered in dump bed trailer trucks at a cost of $12.50/ton. Typically the wood

TABLE 4. MISSOURI FOREST PRODUCTS INDUSTRIES NEAR ROLLA, MISSOURI

WITHIN X MILES	TOTAL AND TYPE OF INDUSTRIES				
	A	B	C	D	E
50	63	15	9	1	1
40	40	9	6	--	1
30	25	2	6	--	1
25	22	1	5	--	1
20	9	1	3	--	--
10	5	1	--	--	--

Key:
- A Sawmills (100,000 board feet per year minimum)
- B Pallet Plants
- C Stave Mills
- D Heading Mills
- E Flooring Mills

chips are hauled in standard cargo trailer but the University doesn't have unloading facilities for the trailers. With this in mind, the bid requested they be hauled and delivered in a self-unloading trailer. This requirement added to the price of the product and also restricted the bids to those people having self-unloading equipment.

Since the time of the bid for the wood chips, the industry has started using trailers with live bottoms. They are much cheaper than the dump beds, and their use could lower the delivery price for the wood chips. The wood chip price, as suggested by the Green Mountain Study (7), was $10 to $15/ton projected so the cost was in the proper range.

At the same time, bid prices for bark delivered in the same fashion were obtained by the University. They were $3.90 ton/ delivered. The hauling distance was approximately 45 miles.

The coal used in the study, as well as the coal used in the everyday running of the plant is delivered by self-unloading trucks. The coal is pre-blended in St. Louis and delivered to Rolla ready for use. The coal cost is $37.53/ton. The cost of the fuels per million Btu was;

coal	$1.56/$10^6$ Btu
wood chips	$1.04/$10^6$ Btu

bark $0.35/10^6$ Btu

If the wood could be used with approximately the same efficiency as the coal, the potential for savings is pointed out in the cost per unit energy quantity given. The efficiency and firing characteristics are defined in the preceding chapters. The availability of the wood product discussed in this chapter seems to be without problem.

FUEL HANDLING

Once the fuel, either coal or wood, is delivered, it is stockpiled separately in the coal yard to be used as needed. The fuel used for study was either coal or a blend by volume of wood chips and coal. The volume measure was simply the bucket of the front-end loader used to transport fuel to the power plant from the stockpile. The initial preparation for a test was the decision of the volume ratio to be used and the quantity necessary for the test. When the ratio was given to the front-end-loader operator he obtained the necessary volumes of wood and coal. These volumes were dumped in an open area of the coal yard and then the volumes were wind rowed. The wind rows were passed through several times to mix the fuel. This operation seemed to work well and there weren't any problems with inconsistent blending, at least not in terms of the mixing operation.

The blended fuel was then moved to the coal pit where it was carried by a bucket conveyor to a segrated bunker in the top of the plant. The normal bunker, which has approximately a 60-ton capacity, was divided to allow for the storage of approximately 15 tons of the blended fuel.

At this point the fuel was available to the weigh lorry of the plant to be weighed and supplied to the boiler as fuel. This pattern of fuel handling is defined by the block diagram, Figure 2.

The weights of the fuel were defined from the volume ratios and from weighing representative samples of the fuels. The fuel supplied was always weighed and records of these weights kept.

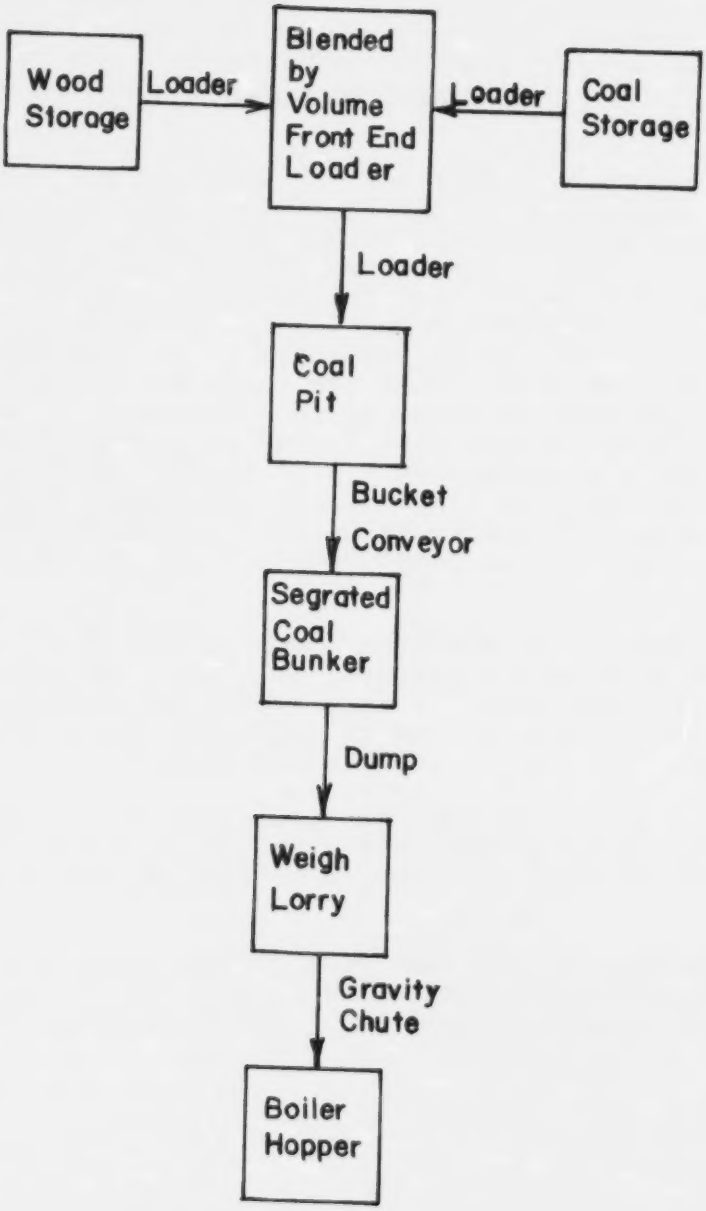


Figure 2. Fuel Handling Diagram

FUEL FIRING

The power plant's function is to be a heating plant for the University, supplying steam to heat and cool the buildings of the campus. The plant at one time was responsible for providing both the electrical and heating needs of the campus and still has that capability. The plant's role was important to the project because the test runs were only made when there was adequate heating load. The test boiler was always run in conjunction with another boiler in the plant. The two boiler combination insured that a loss of boiler load on the test boiler would not interrupt the campus heating system. The two boilers also required an increased plant load to adequately load both boilers. This load condition restricted the testing to fixed periods of time and weather. A boiler load of greater than 5,000 lb/hr (2277 Kg/hr) was the goal in all the testing.

All the tests performed were undertaken on boiler No. 2. The No. 2 boiler was a small 18,000 lb/hr (8,200 Kg/hr), 150 psig (103.4 N/cm^2), saturated steam boiler equipped with a chain-grate stoker. The boiler has no heat traps, superheaters, or pollution equipment. A sketch of the boiler is shown in Figure 3. The fuel was supplied by the fireman from the coal lorry. Before he dumped the fuel into the hopper of the boiler, he weighed it and recorded the weight. The fuel, which was in the hopper, flowed onto the flat bed or chain as it moved into the boiler. The speed of the chain was determined by the steam demand or, if the boiler was set to manual control, the speed was determined by the stoker speed setting. The energy supplied to the boiler was completely a function of the speed of the chain and the depth of the fuel bed, assuming that amounts of combustion air were satisfactory. The fuel bed depth was controlled by the gate shown in Figure 3. The operation manual recommends a thick bed of fuel and a slow chain, but with the blended fuel it could only be partially realized. The situation was apparent when an equivalent fuel bed of blended fuel was calculated from a ratio using the normal coal bed thickness of 4 (10.16 cm) to 4.5 (11.43 cm) inches. The calculation was made assuming the same chain velocity for both fuels

$$t_b = \frac{t_c \cdot L \cdot HHV_c \rho_c}{L \cdot (HHV_c x + HHV_w y) \rho_m}$$

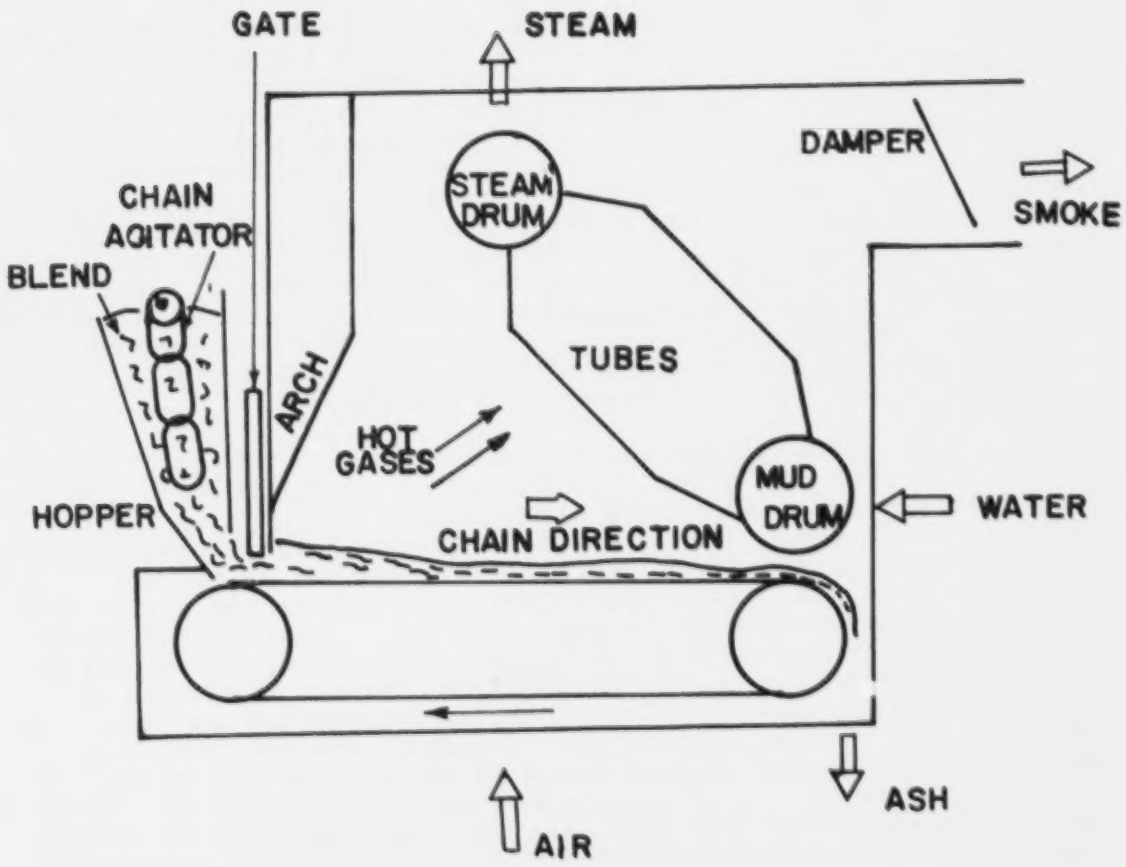


Figure 3. Boiler Sketch

where:

t_b - thickness of the blend bed (in)
t_c - thickness of the normal coal bed (in)
L - width of the chain (in)
HHV_c - Higher Heating Value of coal (Btu/lb)
HHV_w - Higher Heating Value of wood (Btu/lb)
x - pounds of coal/pound of mixture
y - pounds of wood/pound of mixture, and
ρ_c/ρ_m - density ratio coal to mixture.

For a blend of 1 wood by 1 coal, x was 72% and y was 28%, so t_b would be;

$$t_b = \frac{4" \times 60" \times 11{,}500 \text{ Btu/lb } (\frac{1800}{1250})}{60" \times (11{,}500 \text{ Btu/lb} \times .72 + 7000 \text{ Btu/lb} \times .28)}$$
$$= 6.5 \text{ inches } (16.51 \text{ cm}) \qquad (1)$$

The boiler was limited to a 7-inch (17.78 cm) opening of the gate so it was quite apparent that the gate was close to the limit of bed thickness. For a fuel blended 2 wood by 1 coal, the bed thickness would be;

$$t_b = \frac{4" \times 60" \times 11{,}500 \ (\frac{1800}{1066})}{60" \times (11{,}500 \text{ Btu/lb} \times 0.54 + 7{,}000 \times .46)}$$
$$= 8.23 \text{ inches}$$

This thickness wasn't realizable so the only other way to increase the energy input was to run the chain faster. In all cases where the blend was used even with large gates 6 to 7 inches, the chain was always run faster than with all coal with a 4 inch gate. The ignition of the fuel was provided by the ignition arch (Figure 3) of the boiler and the mechanism for ignition was the radiant energy from the arch. In the operation it was desirable to provide for ignition as soon as the fuel flowed out from under the gate, but it was also very important to keep it external from the gate itself.

When the blend was first run with these high gates, the results and experience pointed to ignition problems from both the gate settings and the low ignition temperature of the wood. The problem most frequently encountered was burning under the gate of the boiler.

As one examines the ignition difficulties it is apparent that the problem was most pronounced in the entrance corners.

The burning under the gate would start in the corners and then spread to the total length of the gate. There were probably several reasons for this. One of the reasons was the boiler construction itself; there was a point of stagnation in the fuel flow for gates above 5 inches. This point was on the entrance corners of the boiler as the fuel flowed under the gate. The ignition problem was also experienced with coal but not as frequently. With this in mind, a modification was undertaken to solve the problem in the corners. The boiler hopper was segrated by placing subdivisions in each end of the hopper shown in Figure 4. This modification provided three compartments: dimensions looking at the front of the boiler are 3 inches, 54 inches, and 3 inches. The pure coal was placed in the outside compartments and the blend in the middle compartment, the fuel as supplied to the boiler would look like Figure 5. With this fuel-firing pattern the corners had pure coal with ignition and flow properties of coal. As experience was gained, coal would only be fired in the corners if the fuel was difficult to burn, quite often the corners would be fired with the blend or left empty cooling the corner areas.

Another problem relating to the ignition problem was the fuel bridging in the boiler hopper. The converging shape of the hopper was fine for coal but was difficult for the flow of wood. As the bridging occurred, the fuel fell away from the gate providing a low energy input. The lack of fuel on the chain also allowed for ignition under the gate since it wasn't sealed with fuel. In order to prevent the bridging condition, a cam shaft was supported by bearings across the top of the hopper (Figure 4). This cam shaft was driven by a variable speed, 3/4 horsepower electric motor through a 10/1 speed reducer. There were six cams on the shaft and from each cam a heavy chain was hung. As the shaft rotated, it provided the chains with a 1 1/4 inch travel. The chains were hung in the fuel hopper providing agitation to the blended fuel. The agitation prevented the bridging in the hopper. Again as experience was gained the chains would frequently not be used, especially if the fuel was wet and difficulty was experienced providing for the combustion air.

The firing was normally started with a 6 to 6.5-inch gate setting and stoker speed was a function of the load desired. The boiler was always fired with the boiler controls in the manual position. With manual control, the loading was a base load condition requiring the other boiler to accept most of the load swings.

The input combustion air was controlled by the fan and locked into a constant setting. The boiler was equipped with a force-draft fan and loovers on the intake to the fan controlled the amount of air. At the same time, the damper on the boiler stack was closed more than when operating on coal. In

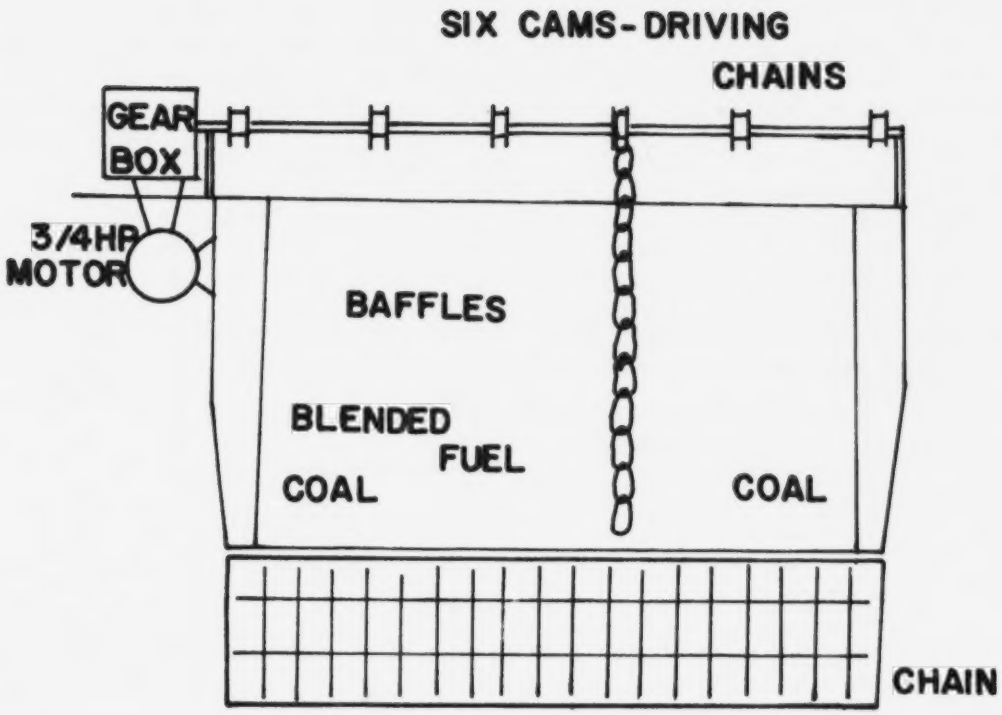


Figure 4. Boiler Modifications

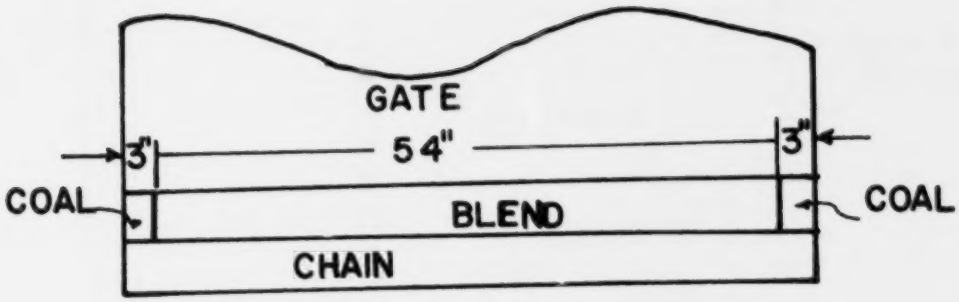


Figure 5. Fuel Supply Sketch

combination, the force-draft fan and damper were controlled to maintain the boiler at the point where it would almost be at zero gauge pressure. This pressure was sensed by keeping the boiler on the verge of smoking. It typically related to a pressure of -0.01 to -0.05 inches of H_20 vaccuum. With the damper control, the fire could be moved away from and back to the gate, but at the same time, opening the damper tended to cool the boiler allowing for a loss of load. The firing required a delicate balance between stoker speed, damper setting, and gate height, and most of the time a less porous fuel bed would have been desirable. The excess air was almost always high even when firing with pure coal. The overfire air was normally kept constant and didn't seem to strongly influence the firing.

Typically the fuel was dry and ignition very rapid. The fireman had to be very careful not to obtain ignition under the gate or a very short fire with little ability to increase or hold the boiler load. As the fireman gained experience with the fuel the firing problems tended to become easier to handle. The boiler consultants made the measurements to cut a cam to run the boiler system automatically but the cam was not fabricated.

FUEL TEST (MIDWEST RESEARCH INSTITUTE)

A test program was undertaken to describe effects of the use of blended fuel on the effluents and the efficiency with varying blends and different coals (10).

The first test was undertaken during the last week of January and the first week of February of 1977. Field testing was performed by Midwest Research Institute, field sampling team to determine particulate, sulfur dioxide, and nitrogen oxide emissions from the boiler firing the blended fuel and to identify potential hazardous organic materials that may be emitted. In all cases, the goal was to determine if differences occurred in boiler emissions from different blends and as compared to all coal.

For this series of tests, a high sulfur (>3%) coal (River King) was fired alone to establish a baseline, and blends of wood and coal in ratios of 1:1 (30% wood, 70% coal) and 2:1 (46% wood, 54% coal) by volume were compared to the coal baseline. The ultimate analysis of the coal and wood used for this test was given in Table 2.

The sampling of the unit was accomplished through the breeching as shown in Figure 6. Note the No. 2 boiler is connected to the common breeching.

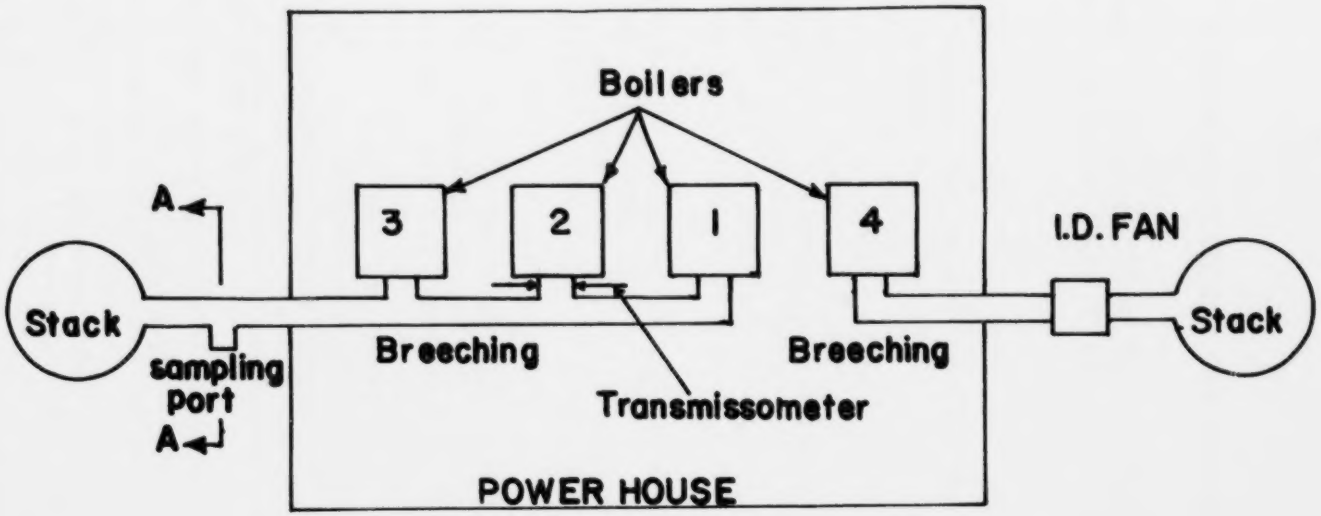


Figure 6. Power Plant Breeching System

SAMPLING AND ANALYSIS METHODS

The sampling and analysis methods used in the test program are individually discussed below along with problems encountered on site.

Sampling

The first task was to perform an EPA Method 1 procedure to ensure the extraction of a representative sample. The sampling locations were numbered 1 to 30 as shown in Figure 7. Locations 31 through 36 were not tested because, on opening the test port, fly ash was found 2 inches deep, 18 inches inside the duct. The nearest upstream disturbance was five equivalent duct diameters away, and the nearest downstream disturbance was two diameters away. By using six sampling locations at the remaining five ports, the conditions for sampling by Method 1 were fulfilled.

Method 2 (EPA) was then performed to determine stack gas velocity and flow rate at the sampling sites. Method 3 (EPA), using an integrated sampling train, was employed to obtain a representative stack gas sample which was analyzed in an Orsat analyzer.

Method 4 (EPA) was initially used to determine moisture content in the stack gas. The measured moisture content of gas on January 26, 27, and 28 was both low and constant; therefore, Method 4 was not performed on subsequent test days (January 31, February 1, 2, 3, and 4). However, the back half of EPA Method 5 was used to measure the moisture content of the stack gas on the latter days. The moisture content remained low enough and consistent enough to insure that all of these determinations were well within isokinetic limits.

To determine particulate emissions, EPA Method 5 was used. On January 26 and 27, isokinetic results were not obtained due to the difficulty of reading the inclined manometer at the very low stack velocities found. Subsequent test runs utilized a more precise manometer to read pressure drop. The level of the precision manometer was checked every time the probe was moved to a new sampling port. Although this ameliorated the difficulties somewhat, precise velocity pressure readings were still difficult to obtain.

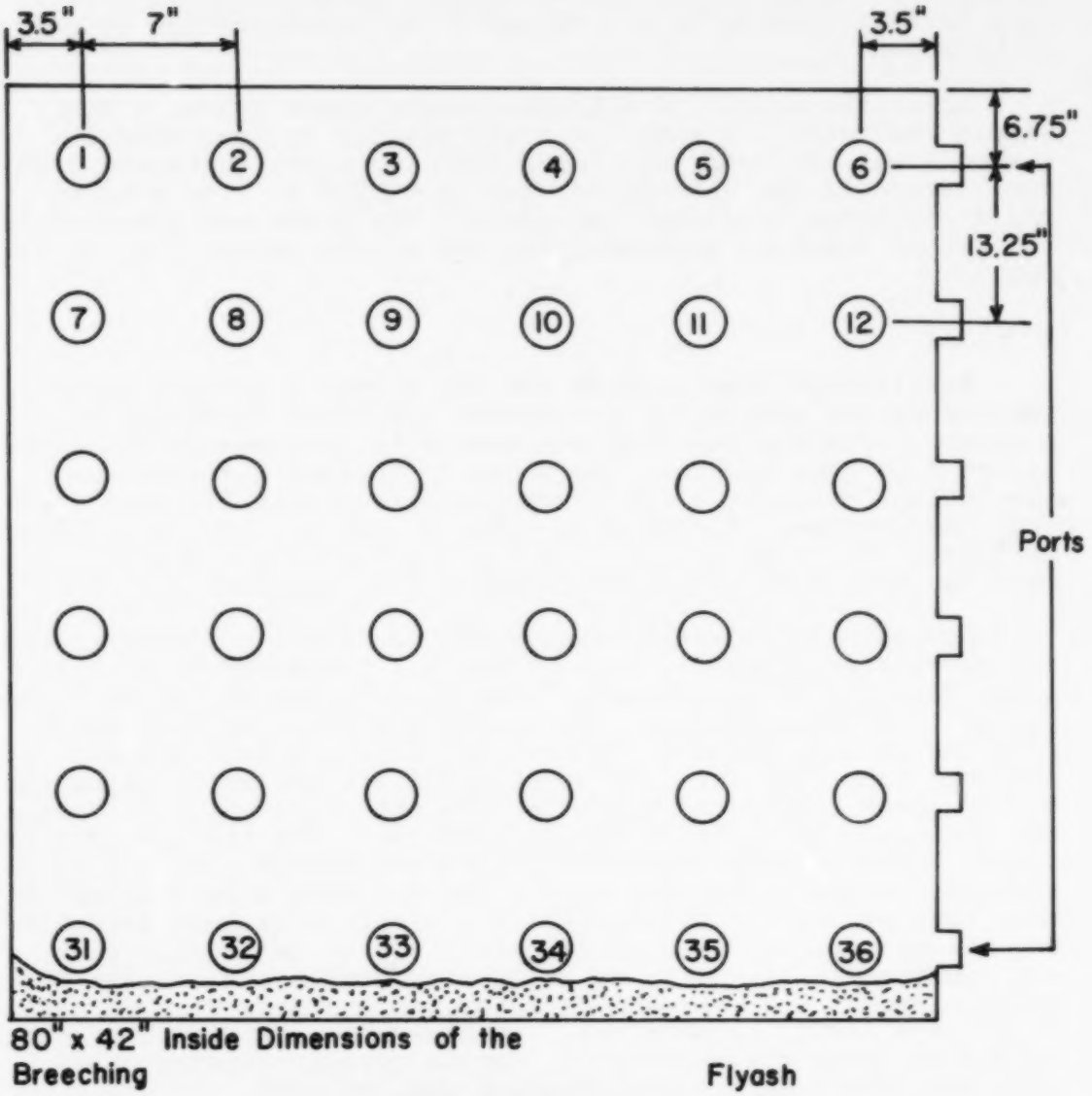


Figure 7. Section of the Sampling Location

As soon as the Method 5 probe cleared the second sampling port, then EPA Method 6 samples for sulfur dioxide were taken with the probe extending halfway into the stack from the second sampling port (third actual port from the bottom of the duct). At the conclusion of the sulfur dioxide sampling, four samples were taken according to EPA Method 7 for determination of oxides of nitrogen.

After the oxides of nitrogen samples were taken, a HCN sample was taken. A sampling train similar to that used in Method 6 was employed, but the midget impingers contained 0.05 N KOH instead of the absorbents used in Method 6. The entire train consisted of midget impingers. The probe was inserted in the second sampling port with its tip at the center line of the duct.

Analysis

Particulate samples from the EPA Method 5 strains were assayed by the analytical precedures specified in Method 5. However, glass fragments were observed in residues of the probe rinses from some samples. In order to correct for this contamination, observed glass fragments were physically separated from the residues, rinsed with acetone, and allowed to dry before weighing. The weights of the glass fragments were subtracted from the corresponding probe-rinse residue weights.

Following gravimetric assays of the Method 5 filter catches for particulate weights, each filter was extracted with three 50-ml portions of cyclohexane. The cyclohexane was added to the filter in a 250-ml beaker, the beaker placed in an ultrasonic bath for 20 min, and then the extract decanted into a vial. All extracts from runs with the sample fuel mixture were composited. Hence, three composited extracts were obtained, which represent the coal-only runs, the 1 wood/1 coal runs, and the 2 wood/1 coal runs. These composited extracts were concentrated to 5.0 ml with a gentle stream of dry nitrogen. The extracts were assayed for four POMs by gas chromatography with electron capture detection. The chromatographic column, 3% Dexsil 300 GC on 100/120 mesh, was operated isothermally at 290°C with a nitrogen carrier flow of 30 ml/min. Injector and detector temperatures were maintained at 245 and 248°C, respectively. A mixed POM standard containing 7,12-dimethylbenz[a]anthracene, benz[a]pyrene, 3-methylcholanthrene, and dibenz[a,h]anthracene was utilized.

Samples were prepared for cyanide assay by distillation according to standard procedures and were assayed with a cyanide ionspecific electrode.

Samples were assayed for NO_x by procedures described in EPA Method 7.

Samples were assayed for SO_2 by procedures described in EPA Method 6.

Aliquots of coal, wood chips, and 1:1 and 2:1 mixtures of wood chips and coal were submitted to Industrial Testing Laboratories, Kansas City, Missouri, for proximate and ultimate analyses.

RESULTS AND DISCUSSION

The results of the test program are presented in Tables 5 and 6. Table 5 displays the measured or uncorrected values while Table 6 displays results corrected for anisokinetic test conditions and low-flue gas velocities. These corrections are discussed next.

Discussion of Test Results

Natural draft-flue gas circuits are inherently unable to overcome large resistances to gas flow. As a consequence, gas velocities must be kept very low in order to minimize the pressure drop due to skin friction. The flue gas velocity in the breeching at Rolla was only about 500 ft/min which corresponds to a velocity pressure of $\cong$ 0.01 in of water. These low values as well as the turbulent, fluctuating nature of low in real systems, make the manometer readings unreliable.

In order to overcome these difficulties, the flue gas flow-rate was calculated for each test from the Orsat analysis of the specific fuel mixture used for the test. It is necessary to use the Orsat analysis of the sampling location because the flue gas composition is not constant throughout the system due to in-leakage of ambient air. Table 7 compares measured and calculated flue gas flow-rates at the sampling location.

The calculated flue gas flow-rates were used as the basis for correcting the measured pollutants. Because it is not necessary to sample gaseous pollutants isokinetically, the measured gaseous concentrations are unaffected by errors in flue gas flow-measurement; however, in calculating the total weight rate of pollutant from the concentration, the corrected flue gas flow-rate does make a difference.

The measured particulate concentration was corrected for anisokinetic samplings by using a technique suggested by Badzioch (11). His method is summarized by Equation 2.

$$C = Cs\left[\frac{\alpha V}{Vs} + (1 - \alpha)\right]^{-1} \quad \text{where:} \qquad (2)$$

C = true fly ash concentration

Cs = sampled fly ash concentration

TABLE 5. TEST RESULTS (UNCORRECTED)

	Coal only			
		Run No. 1	Run No. 2	
Particulate	1/28/77	2/2/77	2/2/77	Avg
$lb/10^6$ Btu	0.1776	0.371	0.159	0.236
gr/dscf	0.0312	0.0463	0.0207	0.033
lb/hr	2.21	3.04	1.31	2.19
lb/lb steam	3.09×10^{-4}	5.28×10^{-4}	2.27×10^{-4}	3.55×10^{-4}
SO_2				
$lb/10^6$ Btu	2.26	2.7	2.03	2.33
ppm	340	289	225	285
lb/hr (expected)	81.7	53.8	53.8	63.1
lb/hr (measured)	28.11	22.21	16.65	22.32
measured/ expected	0.34	0.41	0.31	0.35
lb/lb steam	3.9×10^{-3}	3.8×10^{-3}	2.9×10^{-3}	3.5×10^{-3}
NO_x				
$lb/10^6$ Btu	0.19	0.28	0.20	0.22
ppm	40.85	41.6	31.5	38
lb/hr	2.43	2.29	1.67	2.13
lb/lb steam	3.4×10^{-4}	4.0×10^{-4}	2.9×10^{-4}	3.4×10^{-4}
HCN* ($\mu g/ft^3$)	-	-	-	-
Methane (ppm)	1.3	1.7	1.4	1.5
Acetylene, ethylene, and ethane (ppm)	0.15	0.2	0.1	0.15
Formaldehyde (ppm)	0.6	0.6	0.9	0.7
Propane (ppm)	1.3	1.5	0.8	1.2
Methanol and acetaldehyde (ppm)	0.5	trace	-	<0.5

* Below detection limits

TABLE 5 (continued)

	Coal only			
		Run No. 1	Run No. 2	
	1/28/77	2/2/77	2/2/77	Avg
Ethanol, butanes, and butenes (ppm)	0.2	trace	-	<0.2
Total HC (ppm)	4.05	≅4	-	≅4.25
7,12-dimethyl-benz[a] anthracene* (ng/scf)	-	-	-	<14
benz[a]pyrene* (ng/scf)	-	-	-	<5
3-methylcho-lanthrene* (ng/scf)	-	-	-	<7
dibenz[a,h]* anthracene (ng/scf)	-	-	-	<37
Boiler				
lb coal/hr	1,083	713	713	836
lb wood/hr	0	0	0	0
lb steam/hr	7,154	5,757	5,757	6,223
10^6 Btu/hr in	12.45	8.2	8.2	9.6
% excess air	40	133	139	104
Steam enthalpy (Btu/hr)/ Fuel heat in (Btu/hr)	0.69	0.84	0.84	0.79
flue gas flow (dscfm)	8,266	7,660	7,402	7,776
flue gas flow (acfm)	13,722	11,989	11,484	12,398

* Below detection limits

TABLE 5 (continued)

	1:1 wood to coal volume ratio			
	Run No. 1	Run No. 2		
Particulate	2/1/77	2/1/77	2/4/77	Avg
lb/10^6 Btu	0.460	0.303	0.363	0.375
gr/dscf	0.0776	0.05736	0.0606	0.065
lb/hr	5.56	3.67	4.14	4.46
lb/lb steam	6.70 x 10^{-4}	4.42 x 10^{-4}	6.42 x 10^{-4}	5.85 x 10^{-4}
SO_2				
lb/10^6 Btu	1.57	1.49	2.35	1.80
ppm	263	262	334	286
lb/hr (expected)	65.9	65.9	61.6	64.5
lb/hr (measured)	19	18.10	26.88	21.32
measured/ expected	0.29	0.27	0.44	0.33
lb/lb steam	2.3 x 10^{-3}	2.2 x 10^{-3}	4.2 x 10^{-3}	2.9 x 10^{-3}
NO_x				
lb/10^6 Btu	0.39	0.28	0.19	0.29
ppm	77.9	62.8	37.8	59.5
lb/hr	4.69	3.37	2.17	3.41
lb/lb steam	5.6 x 10^{-4}	4.1 x 10^{-4}	3.4 x 10^{-4}	4.4 x 10^{-4}
HCN* ($\mu g/ft^3$)	-	-	-	-
Methane (ppm)	2.5	1.8	1.5	1.9
Acetylene, ethylene, and ethane (ppm)	trace	0.5	0.3	<0.4
Formaldehyde (ppm)	0.4	0.7	0.9	0.7
Propane (ppm)	2.2	1.8	2.8	2.3
Methanol and acetaldehyde (ppm)	1.0	0.1	trace	<0.6

* Below detection limits

TABLE 5 (continued)

	1:1 wood to coal volume ratio			
	Run No. 1	Run No. 2		
	2/1/77	2/1/77	2/4/77	Avg
Ethanol, butanes, and butenes (ppm)	0.3	0.2	-	<0.3
Total HC (ppm)	≅6.4	5.1	≅5.5	≅6.2
7,12-dimethyl-benz[a] anthracene* (ng/scf)	-	-	-	<14
benz[a]pyrene* (ng/scf)	-	-	-	<5
3-methylcho-lanthrene* (ng/scf)	-	-	-	<7
dibenz[a,h]* anthracene (ng/scf)	-	-	-	<38
Boiler				
lb coal/hr	863	863	806	844
lb wood/hr	326	326	326	326
lb steam/hr	8,303	8,303	6,438	7,681
10^6 Btu/hr in	12.1	12.1	11.4	11.87
% excess air	156	180	125	154
Steam enthalpy (Btu/hr)/ Fuel heat in (Btu/hr)	0.82	0.82	0.68	0.77
flue gas flow (dscfm)	8,365	7,463	7,977	7,935
flue gas flow (acfm)	14,218	12,426	12,921	13,188

* Below detection limits

TABLE 5 (continued)

	2:1 wood to coal volume ratio			
		Run No. 1	Run No. 2	
Particulate	1/31/77	2/3/77	2/3/77	Avg
lb/10^6 Btu	0.269	0.360	0.331	0.32
gr/dscf	0.0443	0.0478	0.04865	0.0469
lb/hr	3.50	3.49	3.21	3.40
lb/lb steam	4.11×10^{-4}	5.31×10^{-4}	4.81×10^{-4}	4.74×10^{-4}
SO_2				
lb/10^6 Btu	2.19	3.29	2.94	2.81
ppm	310	373	334	339
lb/hr (expected)	61.6	46.6	46.6	51.6
lb/hr (measured)	28.56	31.93	28.57	29.69
measured/ expected	0.46	0.68	0.61	0.58
lb/lb steam	3.3×10^{-3}	4.9×10^{-3}	4.3×10^{-3}	4.2×10^{-3}
NO_x				
lb/10^6 Btu	0.24	0.35	0.27	0.29
ppm	47.9	56	47.4	50.4
lb/hr	3.17	3.44	2.62	3.08
lb/lb steam	3.7×10^{-4}	5.2×10^{-4}	4.0×10^{-4}	4.3×10^{-4}
HCN* ($\mu g/ft^3$)	-	-	-	-
Methane (ppm)	6.0	1.3	1.6	3.0
Acetylene, ethylene, and ethane (ppm)	5.4	0.2	0.5	2.0
Formaldehyde (ppm)	1.6	0.8	0.7	1.0
Propane (ppm)	1.8	1.3	1.0	1.4
Methanol and acetaldehyde (ppm)	0.3	0.8	trace	<0.6

*Below detection limits

TABLE 5 (continued)

	2:1 wood to coal volume ratio			
		Run No. 1	Run No. 2	
	1/31/77	2/3/77	2/3/77	Avg
Ethanol, butanes, and butenes (ppm)	-	-	trace	trace
Total HC (ppm)	≅15.1	≅4.4	≅3.8	≅8
7,12-dimethyl-benz[a] anthracene* (ng/scf)	-	-	-	<13
benz[a]pyrene* (ng/scf)	-	-	-	<4
3-methylcholanthrene* (ng/scf)	-	-	-	<7
dibenz[a,h]* anthracene (ng/scf)	-	-	-	<35
Boiler				
lb coal/hr	797	603	603	668
lb wood/hr	573	418	418	470
lb steam/hr	8,518	6,567	6,567	7,217
10^6 Btu/hr in	13	9.7	9.7	10.8
% excess air	81	341	181	201
Steam enthalpy (Btu/hr)/ Fuel heat in (Btu/hr)	0.78	0.81	0.81	0.80
flue gas flow (dscfm)	9,202	8,538	7,690	8,477
flue gas flow (acfm)	16,068	13,648	12,231	13,982

* Below detection limits

TABLE 6. TEST RESULTS (CORRECTED)

	Coal only			
		Run No. 1	Run No. 2	
Particulate	1/28/77	2/2/77	2/2/77	Avg
lb/10^6 Btu	0.204	0.390	0.170	0.255
gr/dscf	0.0265	0.0438	0.0194	0.0299
lb/hr	2.54	3.20	1.39	2.38
lb/lb steam	3.55 x 10^{-4}	5.56 x 10^{-4}	2.41 x 10^{-4}	3.84 x 10^{-4}
SO_2				
lb/10^6 Btu	3.05	3.11	2.29	2.82
ppm	340	289	225	285
lb/hr (expected)	81.7	53.8	53.8	63.1
lb/hr (corrected)	38.03	25.48	18.80	27.44
corrected/ expected	0.47	0.47	0.35	0.43
lb/lb steam	5.3 x 10^{-3}	4.4 x 10^{-3}	3.3 x 10^{-3}	2.97 x 10^{-3}
NO_x				
lb/10^6 Btu	0.26	0.32	0.23	0.27
ppm	40.85	41.6	31.5	38
lb/hr	3.29	2.63	1.88	2.60
lb/lb steam	4.60 x 10^{-4}	4.57 x 10^{-4}	3.27 x 10^{-4}	4.15 x 10^{-4}
HCN* ($\mu g/ft^3$)	-	-	-	-
Methane (ppm)	1.3	1.7	1.4	1.5
Acetylene, ethylene, and ethane (ppm)	0.15	0.2	0.1	0.15
Formaldehyde (ppm)	0.6	0.6	0.9	0.7
Propane (ppm)	1.3	1.5	0.8	1.2
Methanol and Acetaldehyde (ppm)	0.5	trace	-	<0.5

* Below detection limits

TABLE 6 (continued)

	Coal only			
		Run No. 1	Run No. 2	
	1/28/77	2/2/77	2/2/77	Avg
Ethanol, butanes, and butenes(ppm)	0.2	trace	-	<0.2
Total HC (ppm)	4.05	≅4	-	≅4.25
7,12-dimethylbenz [a]*, anthracene (ng/scf)	-	-	-	<14
benz[a]pyrene* (ng/scf)	-	-	-	<5
3-methylcholanthrene* (ng/scf)	-	-	-	<7
dibenz[a,h]* anthracene (ng/scf)	-	-	-	<37
Boiler				
lb coal/hr	1,083	713	713	836
lb wood/hr	0	0	0	0
lb steam/hr	7,154	5,757	5,757	6,223
10^6 Btu/hr in	12.45	8.2	8.2	9.6
% excess air	40	133	139	104
Steam enthalpy (Btu/hr)/ Fule heat in (Btu/hr)	0.69	0.84	0.84	0.79
flue gas flow (dscfm)	11,186	8,546	8,358	9,363
flue gas flow (acfm)	18,569	13,756	12,967	15,097

* Below detection limits

TABLE 6 (continued)

	1:1 wood to coal volume ratio			
	Run No. 1	Run No. 2		
Particulate	2/1/77	2/1/77	2/4/77	Avg
$lb/10^6$ Btu	0.519	0.354	0.411	0.428
gr/dscf	0.0675	0.0478	0.0527	0.056
lb/hr	6.28	4.28	4.69	5.08
lb/lb steam	7.57×10^{-4}	5.15×10^{-4}	7.27×10^{-4}	6.66×10^{-4}
SO_2				
$lb/10^6$ Btu	2.04	2.09	3.07	2.4
ppm	263	262	334	286
lb/hr (expected)	65.9	65.9	61.6	64.5
lb/hr (corrected)	24.67	25.25	34.99	28.30
corrected/ expected	0.37	0.38	0.57	0.44
lb/lb steam	2.97×10^{-3}	3.04×10^{-3}	5.43×10^{-3}	3.81×10^{-3}
NO_x				
$lb/10^6$ Btu	0.50	0.39	0.25	0.38
ppm	77.9	62.8	37.8	59.5
lb/hr	6.09	4.71	2.82	4.54
lb/lb steam	7.33×10^{-4}	5.67×10^{-4}	4.38×10^{-4}	5.79×10^{-4}
HCN* ($\mu g/ft^3$)	-	-	-	-
Methane (ppm)	2.5	1.8	1.5	1.9
Acetylene, ethylene, and ethane (ppm)	trace	0.5	0.3	<0.4
Formaldehyde (ppm)	0.4	0.7	0.9	0.7
Propane (ppm)	2.2	1.8	2.8	2.3
Methanol and Acetaldehyde (ppm)	1.0	0.1	trace	<0.6

* Below detection limits

TABLE 6 (continued)

	1:1 wood to coal volume ratio			
	Run No. 1	Run No. 2		
	2/1/77	2/1/77	2/4/77	Avg
Ethanol, butanes, and butenes (ppm)	0.3	0.2	-	0.3
Total HC (ppm)	≅6.4	5.1	≅5.5	≅6.2
7,12-dimethylbenz [a]*, anthracene (ng/scf)	-	-	-	<14
benz[a]pyrene* (ng/scf)	-	-	-	<5
3-methylcholanthrene* (ng/scf)	-	-	-	<7
dibenz[a,h]* anthracene (ng/scf)	-	-	-	<38
Boiler				
lb coal/hr	863	863	806	844
lb wood/hr	326	326	326	326
lb steam/hr	8,303	8,303	6,438	7,681
10^6 Btu/hr in	12.1	12.1	11.4	11.87
% excess air	156	180	125	154
Steam enthalpy (Btu/hr)/ Fuel heat in (Btu/hr)	0.82	0.82	0.68	0.77
flue gas flow (dscfm)	10,863	10,442	10,383	10,563
flue gas flow (acfm)	18,464	17,386	16,818	17,548

* Below detection limits

TABLE 6 (continued)

	2:1 wood to coal volume ratio			
		Run No. 1	Run No. 2	
Particulate	1/31/77	2/3/77	2/3/77	Avg
lb/10^6 Btu	0.260	0.341	0.352	0.318
gr/dscf	0.0457	0.0502	0.0455	0.0471
lb/hr	3.38	3.31	3.41	3.37
lb/lb steam	3.97×10^{-4}	5.06×10^{-4}	5.11×10^{-4}	4.71×10^{-4}
SO_2				
lb/10^6 Btu	2.06	2.96	3.35	2.79
ppm	310	343	334	339
lb/hr (expected)	61.6	46.6	46.6	51.6
lb/hr (corrected)	26.76	28.79	32.52	29.36
corrected/ expected	0.43	0.62	0.70	0.58
lb/lb steam	3.14×10^{-3}	4.38×10^{-3}	4.95×10^{-3}	4.15×10^{-3}
NO_x				
lb/10^6 Btu	0.23	0.32	0.31	0.29
ppm	47.9	56	47.4	50.4
lb/hr	2.97	3.10	2.98	3.02
lb/lb steam	3.49×10^{-4}	4.72×10^{-4}	4.54×10^{-4}	4.25×10^{-4}
HCN* ($\mu g/ft^3$)	-	-	-	-
Methane (ppm)	6.0	1.3	1.6	3.0
Acetylene, ethylene, and ethane (ppm)	5.4	0.2	0.5	2.0
Formaldehyde (ppm)	1.6	0.8	0.7	1.0
Propane (ppm)	1.8	1.3	1.0	1.4
Methanol and Acetaldehyde (ppm)	0.3	0.8	trace	<0.6

* Below detection limits

TABLE 6 (continued)

	2:1 wood to coal volume ratio			
		Run No. 1	Run No. 2	
	1/31/77	2/3/77	2/3/77	Avg
Ethanol, butanes, and butenes (ppm)	-	-	trace	trace
Total HC (ppm)	≅15.1	≅4.4	≅3.8	≅8
7,12-dimethylbenz a *, anthracene (ng/scf)	-	-	-	<13
benz a pyrene* (ng/scf)	-	-	-	<4
3-methylcholanthrene* (ng/scf)	-	-	-	<7
dibenz a,h * anthracene (ng/scf)	-	-	-	<35
Boiler				
lb coal/hr	797	603	603	668
lb wood/hr	573	418	418	470
lb steam/hr	8,518	6,567	6,567	7,217
10^6 Btu/hr in	13	9.7	9.7	10.8
% excess air	81	341	181	201
Steam enthalpy (Btu/hr)/ Fuel heat in (Btu/hr)	0.78	0.81	0.81	0.80
flue gas flow (dscfm)	8,624	7,698	8,753	8,358
flue gas flow (acfm)	15,058	12,305	13,921	13,761

* Below detection limits

TABLE 7. COMPARISON OF MEASURED AND CALCULATED FLUE GAS FLOW RATES

	Coal			1:1			2:1		
Run No.		No. 1	No. 2	No. 1	No. 2			No. 1	No. 2
Date	1/28	2/2	2/2	2/1	2/1	2/4	1/31	2/3	2/3
Measured*	8,266	7,660	7,402	8,365	7,463	7,977	9,202	8,538	7,690
Calculated*	11,186	8,546	8,358	10,863	10,442	10,383	8,624	7,698	8,753

* Flue gas flow rate - dscfm

V = true duct velocity at sampling location

Vs = sampling velocity

α = parameter (0.5 recommended by Badzioch for stoker-fired boilers)

The correction of the measured particulate concentration is predicted on the reasonable assumption that, on the average, the ratio of true velocity to sampling velocity at each point will be equal to the ratio of corrected flue gas flow-rate to measured flue gas flow-rate. Therefore, Equation 2 becomes:

$$C = Cs\left[\frac{\alpha Qc}{Qs} + (1 - \alpha)\right]^{-1} \quad \text{where:} \qquad (3)$$

C = true fly ash concentration

Cs = sampled fly ash concentration

Qc = corrected flue gas flow rate

Qs = sampled flue gas flow rate

α = parameter (as before)

These values of particulate were plotted in Figure 8 versus excess air. A least square fit was drawn through the data and the correlation was quite good. A large part of the change in particulate loading can be related to the large changes in excess air. This was especially true in the 1:1 ratio wood to coal. The particulate was also plotted versus weight ratio of coal in the fuel in Figure 9. A least square fit was constructed through this data, and then to correct for excess air, the excess air versus weight ratio was plotted. These data were also fitted with a first order, least square fit. Then by taking the excess air change for the weight ratios of the data times the slope of the particulate-versus-excess air curve, a correction was made to the particulate-versus-weight ratio plot.

The increase in particulate from all coal to 59% coal was approximately 14%, on the corrected curve a change from 0.2916 $lb/10^6$ Btu to 0.33 $lb/10^6$ Btu, respectively.

No consistent increases or decreases were apparent in the NO_x, SO_2, or POMs when increasing amounts of wood chips are substituted for coal. There does appear, however, to be a consistent increase in total hydrocarbon (THC).

It was expected that SO_2 would decrease substantially with increasing amounts of wood fuel. The absence of this expected trend coupled with the low ratios of measured SO_2 to expected SO_2 has cast doubt on the reliability of the SO_2 results. It was initially thought that perhaps the SO_2 concentration was non-uniform across the breeching at the sampling location due to

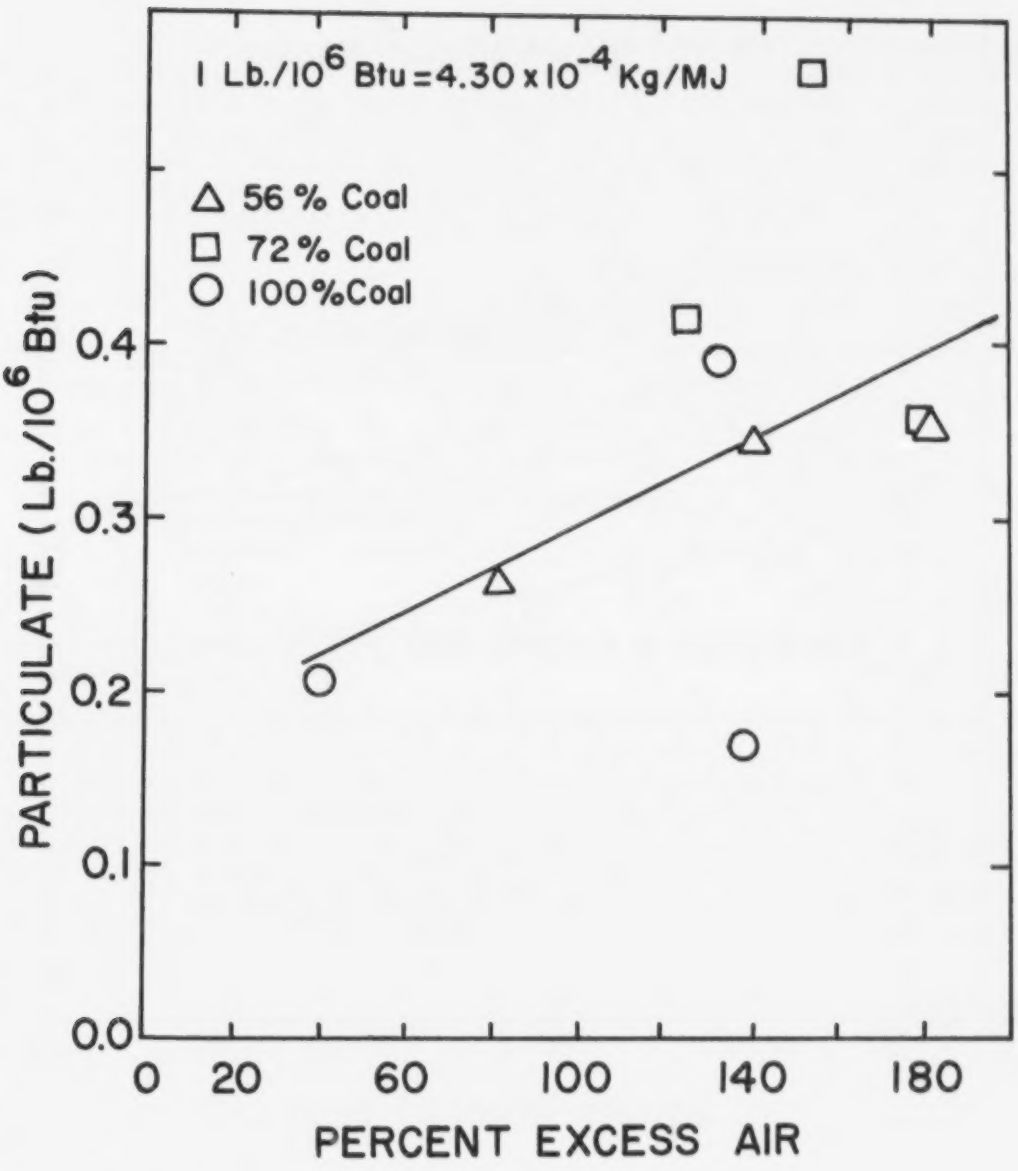


Figure 8. Particulate Loading as a Function of the Excess Air

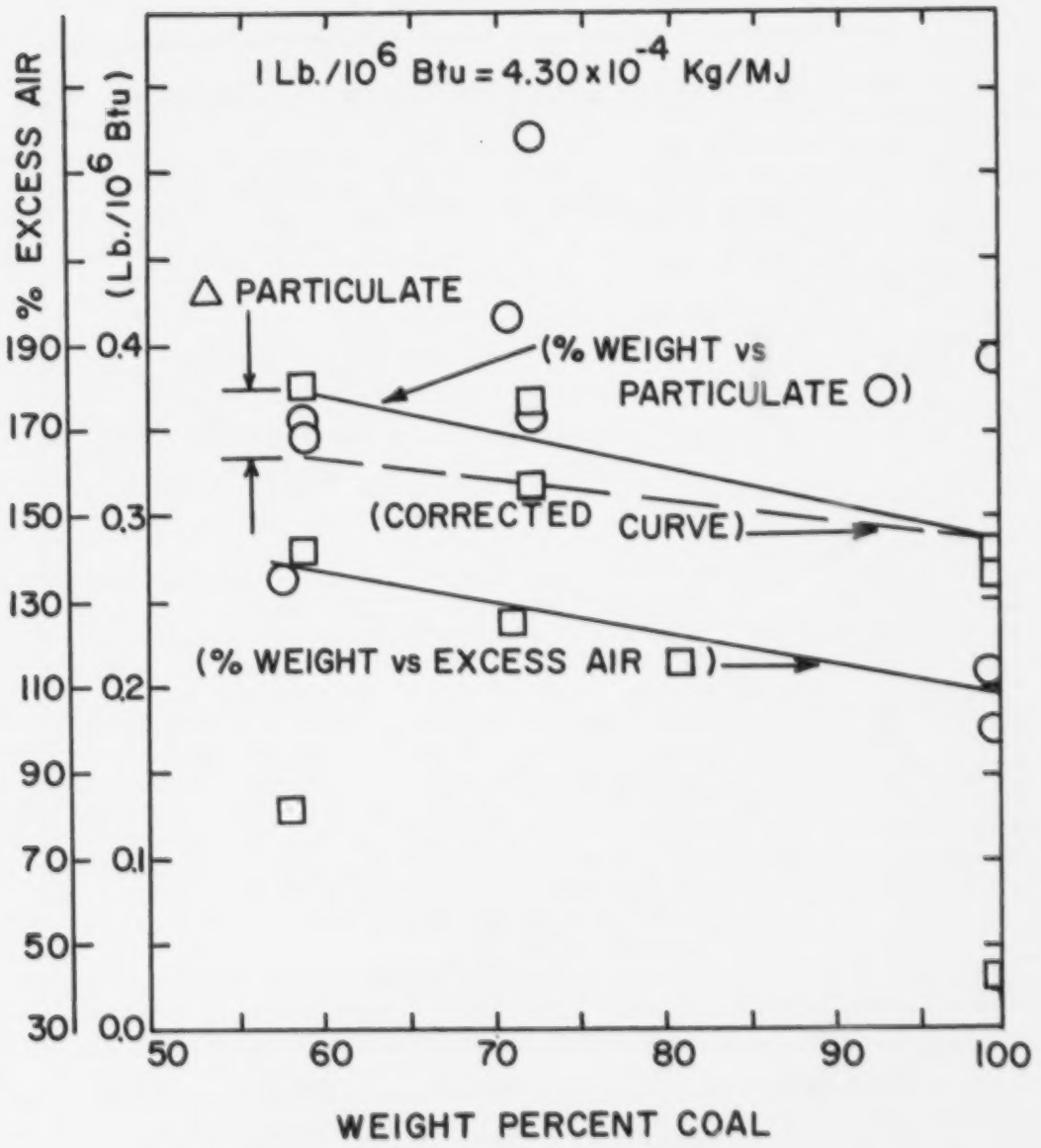


Figure 9. Particulate Correction as a Function of Weight Percent Coal

stratified in-leakage of ambient air. However, a check of the temperature profile and Reynolds number in the breeching at the sampling location indicates that mixing did take place as demonstrated in calculations of these profiles and Reynolds Numbers (12).

An additional basis for comparison of particulate and SO_2 results is provided by a compliance test performed on the boiler in 1974 while firing coal only. Table 8 gives the average of this compliance test compared to the average of the coal-only results from this test program. As can be seen from Table 8, there is agreement on the particulate results, but again, it appears that the current SO_2 results are invalid.

TABLE 8. COMPARISON OF 1974 COMPLIANCE TEST WITH COAL-ONLY RESULTS OF CURRENT PROGRAM

Test dates	1974	1977
Heat input (MBtu/hr)	16.95	9.6
Steam production (lb/hr)	12,310	6,223
Particulate (lb/MBtu)	0.29	0.255
Particulate (gr/scf)	0.065	0.0299
SO_x (ppm)	744	285
SO_x (lb/hr)	65.4	27.44
Measured SO_x/Expected SO_x	1.05	0.43
Sulfur in coal (%)	2.14	3.17
Ash in coal (%)	11.17	11.53

Particle size determination was attempted with impactors during each test; however, the results were invalidated by the build-up of a static electricity charge on the collected sample. This charge build-up prohibited accurate weighing of the small amount of particulate collected (in fact, negative weight gains were detected on some stages).

FUEL TESTING (UNIVERSITY OF MISSOURI-ROLLA)

Further testing of the fuel was undertaken during the months of June, July, and August of 1977 to better define the SO_2 concentrations and nitrogen oxides and particulate effluents. In order to try to avoid the problems of dilution of effluents with air leakage into the breeching, all the measurements were taken at the top of the boiler. The sampling location was the section of breeching connecting No. 2 boiler to the main breeching serving all three boilers; see Figure 6.

Basically three different blends were again fired; 2:1, 1:1, and all coal, for three different coals; see Table 2. An attempt was made to duplicate the steam flows and flue gas temperatures for each run. A steam load of approximately 6000 lb/hr (2733 Kg/hr) was the normal goal. To accomplish this goal, manual control was normally used as with the previous test except for the occasional automatic mode when running with all coal.

During each run, three categories of data were taken. First, a performance comparison of the blended fuels was made using the boiler charts and integrators, and periodic Orsat analyses (every 30 minutes). Second, emissions of sulfur dioxide, nitrogen oxides, and particulate matter were found by continuous monitoring of the flue gases. Finally, daily tests were conducted to determine heating values of the fuels and refuse (bomb calorimeter), sulfur contents of the fuels and refuse (titration), and fuel moisture contents.

The basic system employed to determine the gaseous pollutants in the flue gas involved an electrochemical gas monitor that provided sulfur dioxide and nitrogen oxides concentrations in parts per million on a continuous basis. Upstream, removal of particulate matter was accomplished by a paper filter thimble, and the water vapor removed by an ice bath condenser. Calibration of the instrument using standard sulfur dioxide and nitric oxide calibration of the instrument was performed at least once daily using standard sulfur dioxide and nitric oxide calibration gases. Periodic sampling per EPA Method 6 was performed to verify the accuracy of the instrumentation.

Particulate data was obtained in the form of opacity with a stack-mounted transmissometer. The transmissometer was a fully automated system using a modulated light beam with 3% accuracy. The unit provided a zero and span calibration to the

system automatically every hour. The output was read and recorded every 30 minutes.

ANALYSIS

The analytical technique used to reduce the data was basically a combustion analysis described in many tests on the subject (12-15), including a heat balance of each run made. Modifications to the analysis included a totally dry basis consideration and the use of both carbon dioxide and oxygen Orsat results to determine excess air. The dry basis analysis is desirable, since both the gas monitor and the Orsat apparatus operate essentially on the dry basis.

First, the net composition of the fuel is determined from the volumetric ratio of the wood to the coal and the respective ultimate analyses and moisture contents. By weighing several samples, it was determined that for the coal and wood sizing and moisture contents experienced, a mixture of 50% coal/50% wood by volume corresponds to 72% coal/28% wood by weight. Accordingly, weight fractions for other blends may be calculated, given the volumetric ratio and considering any coal added along the sides of the blended fuel, by the relationship

$$WF_C = \frac{\frac{M_F}{\frac{28}{72} G + 1} + M_C}{M_F + M_C} \qquad (4)$$

where WF_C is the weight fraction of coal in the mixture burned, M_F is the weight of the blended fuel, M_C is the weight of any additional coal that may be added along the sides, and G is the volumetric ratio of wood to coal.

To calculate the effective composition of the fuel fired, the following expression is used for all components except oxygen and hydrogen:

$$Z = Z_C WF_C (1-MC_C) + Z_W (1-WF_C)(1-MC_W) \qquad (5)$$

where Z, Z_C, Z_W are the weight percentages of a component of the net fuel, coal, and wood respectively, MC_C is the moisture content of the coal, and MC_W is the moisture content of the wood. For the oxygen and hydrogen contents,

$$O_2 = \frac{[O_c(1-MC_c) + \frac{800}{9} MC_c]WF_c + [O_w(1-MC_w) + \frac{800}{9} MC_w]}{(1-WF_c)} \quad (5a)$$

$$H_2 = \frac{[H_c(1-MC_c) + \frac{100}{9} MC_c]WF_c + [H_w(1-MC_w) + \frac{100}{9} MC_w]}{(1-WF_c)} \quad (5b)$$

The symbols are the same as in the previous case with O_2 representing the weight percentage of oxygen and H_2 representing the weight percentage of hydrogen.

The refuse contained often times considerable unburned carbon and sulfur. To account for this correction, the carbon and sulfur weight percentages were modified by

$$C_{AB} = C - \frac{\beta}{1-\beta-\gamma} A \quad (6a)$$

$$S_{AB} = A - \frac{\gamma}{1-\beta-\gamma} A \quad (6b)$$

In these expressions, C_{AB} and S_{AB} denote the weight percentages (pound constituent per 100 pounds fuel) actually burned, while C, S, and A are the weight percentages of carbon, sulfur, and ash respectively in the composite fuel. As calculated previously, β symbolizes the weight fraction of carbon in the refuse, and γ symbolizes the weight fraction of sulfur in the refuse.

Next, the theoretical amount of oxygen required per 100 pounds of fuel is found by a molar balance and the ideal gas law.

$$V_{TO} = \frac{RT}{P} \left(\frac{C_{AB}}{12} + \frac{H_2}{4} - \frac{O_2}{32} + \frac{S_{AB}}{32}\right) \quad (7)$$

where V_{TO} is the volume of theoretical oxygen required per 100 pounds of fuel, R is the ideal gas constant (1,545 lbf-ft/lb-mole-^{o}F), T is the absolute temperature in degrees Rankine, and P is the pressure, in pounds per square foot. The corresponding volume of nitrogen accompanying the oxygen (per 100 pounds of fuel) is given by V_{TN}, where

$$V_{TN} = \frac{79}{21} V_{TO} \quad (8)$$

The theoretical volume of dry combustion products plus the volume of nitrogen from the fuel plus the volume of nitrogen from the combustion air is then equal to the theoretical dry

flue gas volume per 100 pounds of fuel, or

$$V_{CT} = \frac{RT}{P} \left(\frac{C_{AB}}{12} + \frac{S_{AB}}{32} + \frac{N_2}{28}\right) + V_{TN} \tag{9}$$

Here, V_{CT} represents the theoretical dry flue gas volume per 100 pounds of fuel, and N_2 represents the pounds of nitrogen per 100 pounds of fuel.

The actual volume of dry flue gas per 100 pounds of fuel can be written as V_{ACT}, where

$$V_{ACT} = V_{CT} + V_{EA} \tag{10}$$

Here, V_{EA} is the volume of excess air introduced into the system per 100 pounds of fuel. VCT is calculated assuming stoichiometric fuel mixtures, but V_{EA} may be calculated from the Orsat analysis of the flue gas. The amount of excess air in this boiler is considerable, often over 120%, and consequently the amount of carbon monoxide present is extremely small, and may be neglected. Determination of V_{EA} was done considering both the carbon dioxide and oxygen percentages, and results averaged. The following formulas were used.

$$\% \ CO_2 = \frac{\frac{RT}{P} \left(\frac{C_{AB}}{12} + \frac{S_{AB}}{32}\right)}{V_{CT} + V_{EA}|_{O_2}} \tag{11a}$$

$$V_{EA}|_{CO_2} = \frac{\frac{RT}{P} \left(\frac{C_{AB}}{12} + \frac{S_{AB}}{32}\right) - V_{CT} \ (\% \ CO_2)}{\% \ CO_2} \tag{11b}$$

$$\% \ O_2 = \frac{21 \ V_{EA}|_{O_2}}{V_{CT} + V_{EA}|_{O_2}} \tag{12a}$$

$$V_{EA}|_{O_2} = \frac{V_{CT}(\% \ O_2)}{21 - \% \ O_2} \tag{12b}$$

$$V_{EA} = \frac{V_{EA}|_{CO_2} + V_{EA}|_{O_2}}{2} \tag{13}$$

Here, % CO_2 and % O_2 are the volumetric percentages of carbon dioxide and oxygen respectively from the Orsat analysis of the flue gas. $V_{EA}|_{CO_2}$ and $V_{EA}|_{O_2}$ represent the volume of excess air present per 100 pounds of fuel from carbon dioxide and oxygen analyses respectively. Note that the weight percentage of sulfur actually burned appears in Equations (11a) and (11b). The reason for this is that the Orsat apparatus absorbs both carbon dioxide and sulfur dioxide during the carbon dioxide measurement.

It was found in this research that the combined results of a carbon balance and an oxygen balance tended to average but errors made in reading the Orsat, and gave satisfactory results.

Now that the volume of dry flue gas per 100 pounds of fuel has been calculated, the fuel rate in pounds per hour may be used to calculate the volumetric flow rate of the dry flue gas. When the pressure and temperature are taken as instrument conditions, the volumetric flow rate may be combined with the concentration of the pollutants and the ideal gas law to yield the mass flow rate of the pollutant.

The heating rate may be computed by considering the dry, higher heating values of the coal and wood, the fueling rate, and the moisture contents and weight fractions.

$$HR = FR\ [HHV_c(1-MC_c)WF_c + HHV_w(1-MC_w)(1-WF_c)] \qquad (14)$$

where HR denotes the heating rate in unit energy input per unit time, HHV_c and HHV_w represent the dry higher heating values of the coal and wood respectively. Fueling rate (FR) is unit weight of fuel per unit time.

RESULTS AND DISCUSSION

The results for gaseous and particulate emissions are graphically presented in Figures 10, 12, and 13.

Sulfur dioxide emissions, as plotted in Figure 10, show a consistent decrease in the pounds per million Btu emissions index as the percentage of wood, increases in the fired fuel. The solid lines indicate the results of the experimental data while the dashed lines represent the expected data based on the sulfur actually burned. Sulfur accountability was rather encouraging, deviating about 17% at the most from the ideal or expected value. The curve in Figure 11 was an attempt to normalize the data. Each point was divided by an all coal value for that set of coal runs and the expected curve was the normalized expected curve for the 3.12% sulfur coal. This was identified as coal No. 2 in Table 2.

The nitrogen oxides data, presented in Figure 2, were scattered as expected, since formation of nitrogen oxides is basically a function of flame temperatures, residence time, and percent excess air, the first two of which are unaccounted for variables in this testing program. Due to this uncertainty, no relationship between nitrogen oxides emissions and the wood content of the fired fuel could be determined. The emissions were also considered versus percent excess air, and moisture content, with no success. A complete study of the nitrogen oxides emissions would require additional experimental considerations not included in this work.

The particulate emissions, considered as opacity, are plotted versus excess air in Figure 13. The presentation of the data in this manner presents an almost linear relationship between opacity and excess air. The linear relationship to excess air was the same as that demonstrated by the particulate data taken by Midwest Research Institute. Again the opacity versus weight percent was plotted in Figure 14 for all three fuels. This data was fitted with least square linear approximation as plotted. In order to investigate the effect of the excess air, the opacity versus weight was plotted in Figure 15 for 2.44% sulfur coal. Again, the change in the excess air from the linear curve was found to be 63% in going from 59% coal to all coal on the curve. Multiplying this change in excess air by the slope of the opacity versus excess air curve (0.211) produces a Δopacity due to excess air of 1.33.

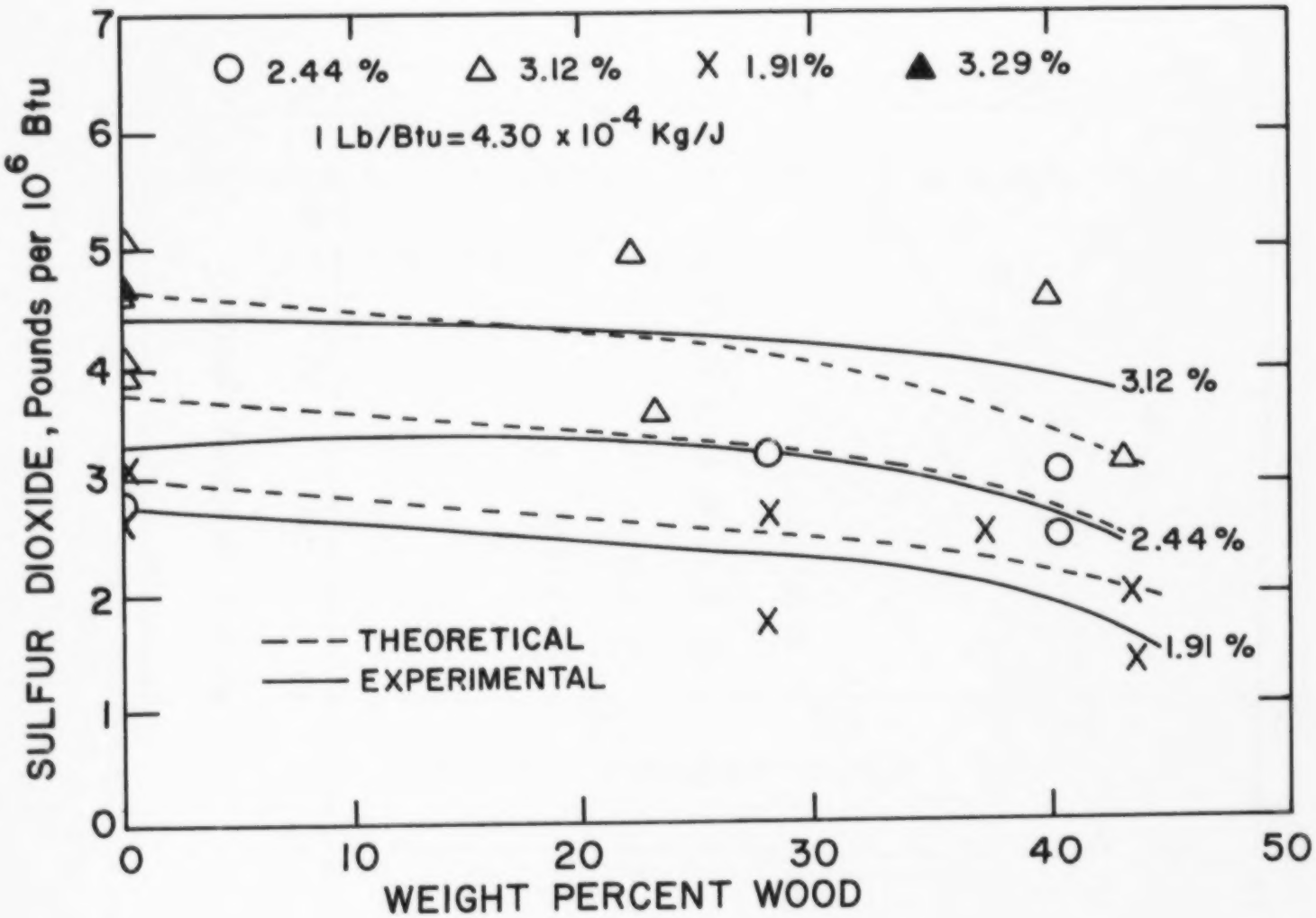


Figure 10. Sulfur Dioxide Emissions as a Function of Fuel Blend and Coal Sulfur Content

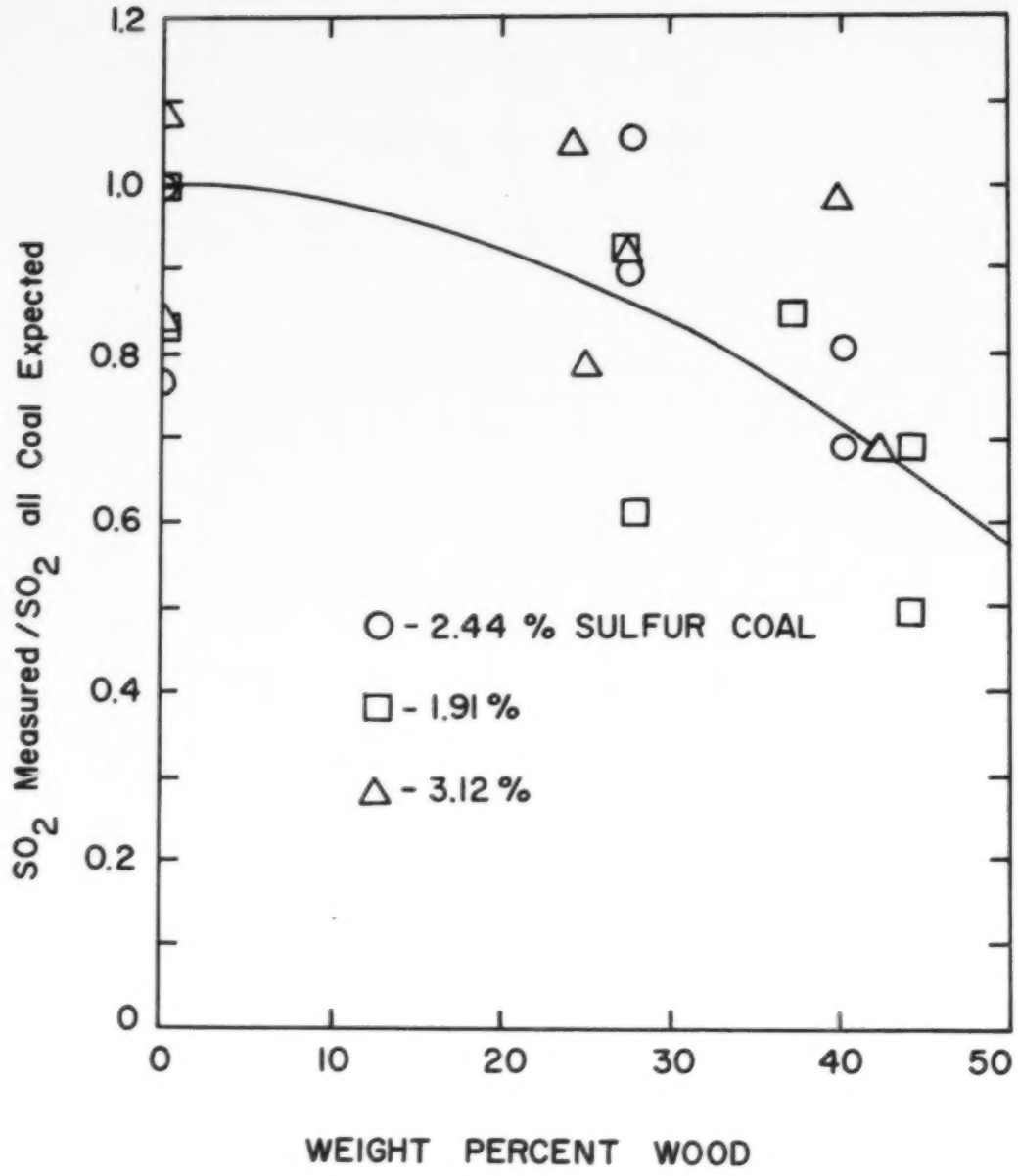


Figure 11. Normalized Sulfur Dioxide Output as a Function of Wood Percent

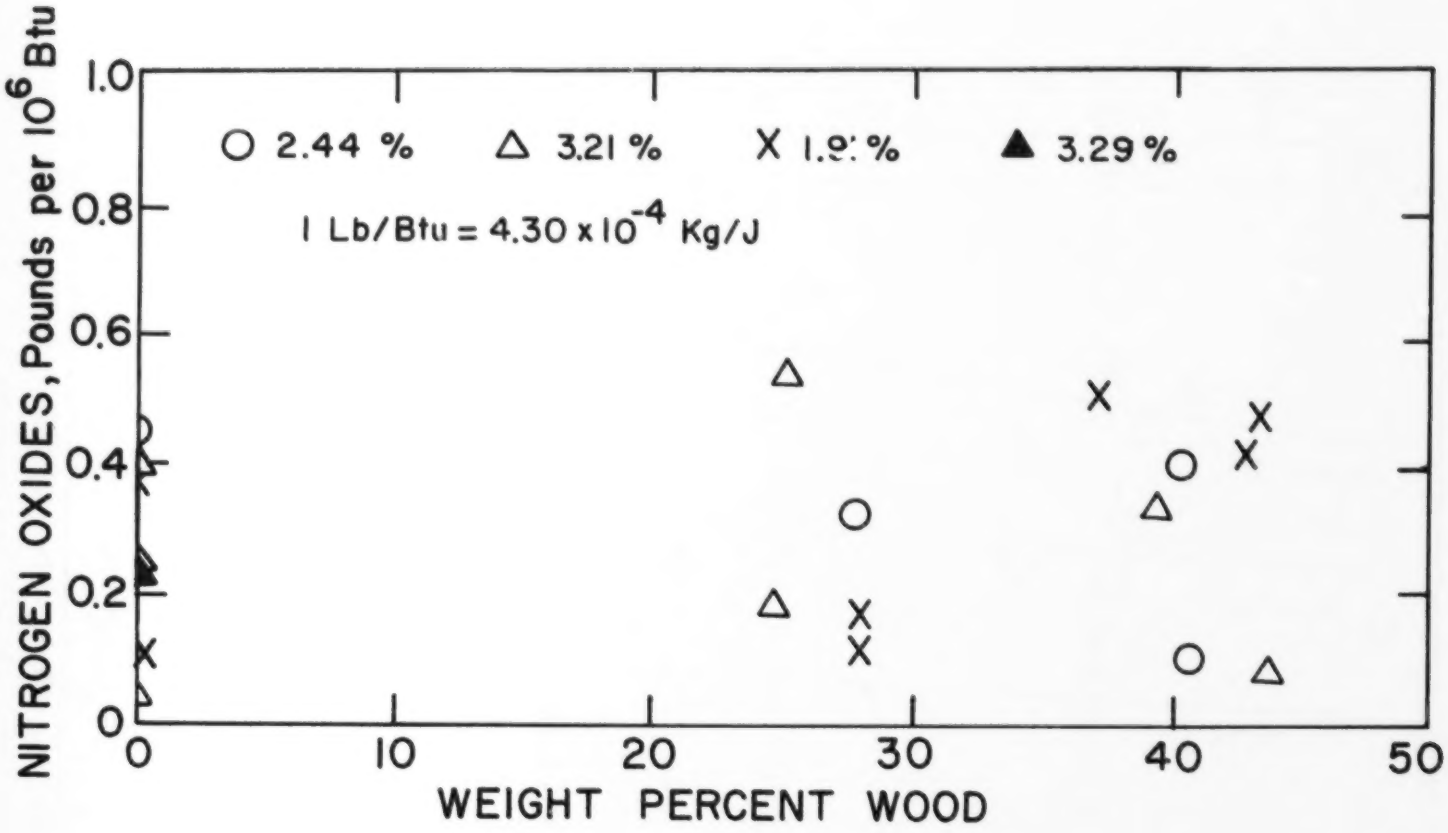


Figure 12. Nitrogen Oxides Emissions as a Function of Fuel Blend

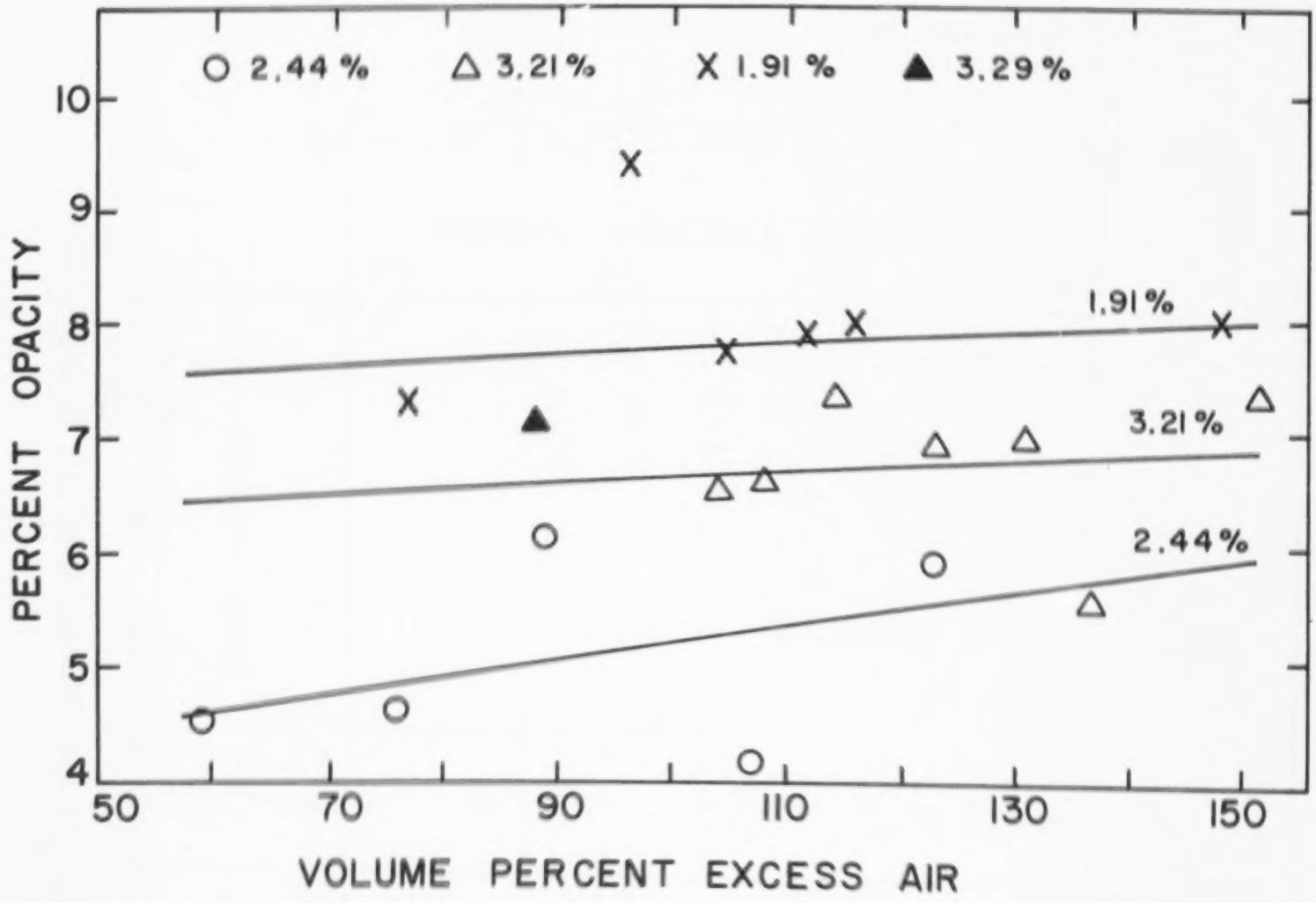


Figure 13. Opacity of Flue Gas as a Function of Excess Air and Coal Sulfur Content

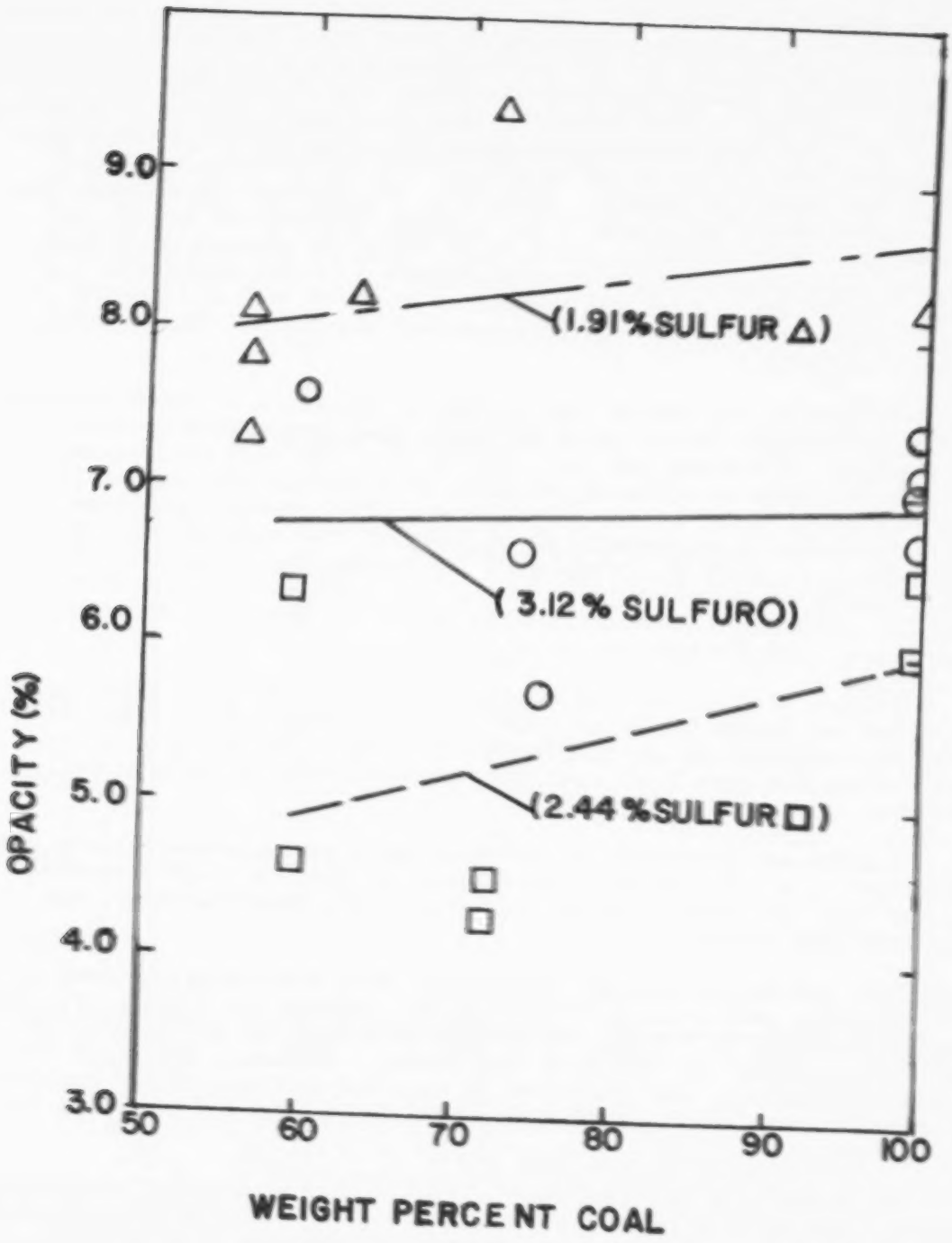


Figure 14. Opacity as a Function of the Weight Percent of the Coal

Subtracting this from the curve in Figure 15 produced a constant opacity for the weight variation in coal from 59% to 100%. Suggesting no change in the particulate loading over the weight percent range, it was assumed the other two fuels would have similar behavior. This behavior was also suggested by the MRI data. To link the Midwest Research results to the results of the summer testing program, tests of the River King coal was made. The opacity readings, the SO_2, NO_x levels were taken for this coal. The run produced an average opacity of 7.1 at an excess air value of 88%. With this value of excess air, the particulate value was found from Figure 8. The value was 0.282 lb/10^6 Btu. The SO_2 value for the run was 4.7 lb/10^6 Btu accounting for 98% of the expected amount and the NO_x was 2.2 lb/10^6 Btu.

To define the boiler performance operation on the different coals and blends boiler heat balance data was measured and presented. The experimental results for the various losses considered were plotted as percent loss versus the weight percentage of wood in the fuel fired. The results achieved were essentially as expected, in view of the natures of the coal and wood. It must be remembered, however, that presentation of the results as percentages might prove deceptive since the net heating value of the fuels change with the wood and moisture content of the composite fuels.

Figure 16 depicts the decrease in both dry gas loss and loss to unburned combustible as wood content increases. These are logical results, since the weight of both combustion products and refuse per pound of fuel decrease with increasing wood content.

Presented in Figure 17 are the various moisture losses. As expected, the most severe dependence on wood content appeared in the fuel moisture losses, and the least dependence in the air moisture losses.

The net efficiencies (excluding what are normally denoted as radiation and unaccountable losses) appear in Figure 18. It is interesting to notice the slight increase in efficiency as the wood content in the fuel increases. However, in terms of steam generation, the decrease in the net heating value resulting from additional wood in the fired fuel offsets any increase in efficiency.

This fact is pointed out in Figure 19, where the performance factor, defined as pounds of steam per pound of fuel is plotted versus the weight percentage of wood in the fuel. A slight decrease with increasing wood content is evident, as expected. However, considering the fact that the cost of coal is two to three times the cost of wood waste, the results are rather encouraging.

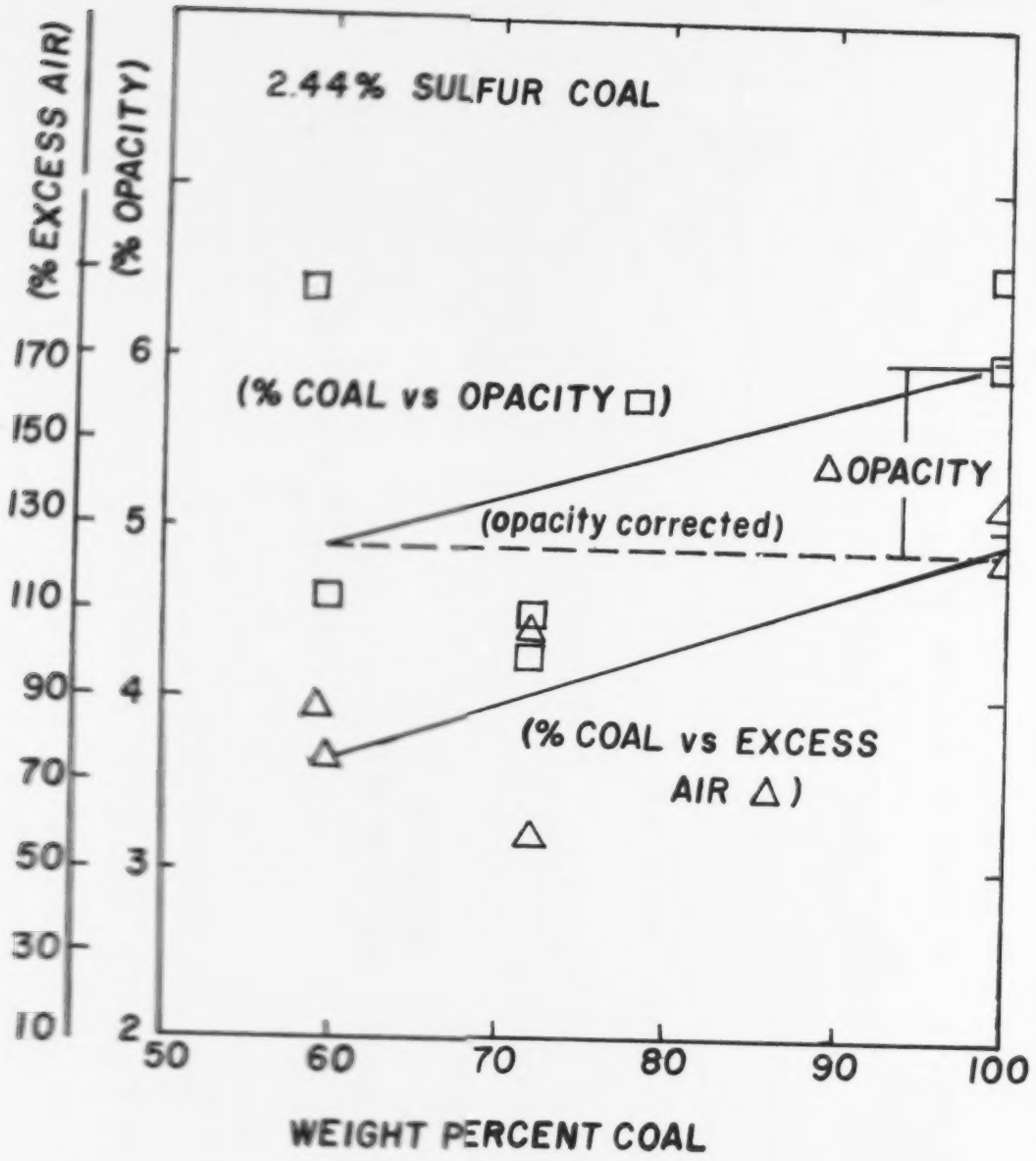


Figure 15. Opacity Correction Curve Function of the Weight Percent Coal

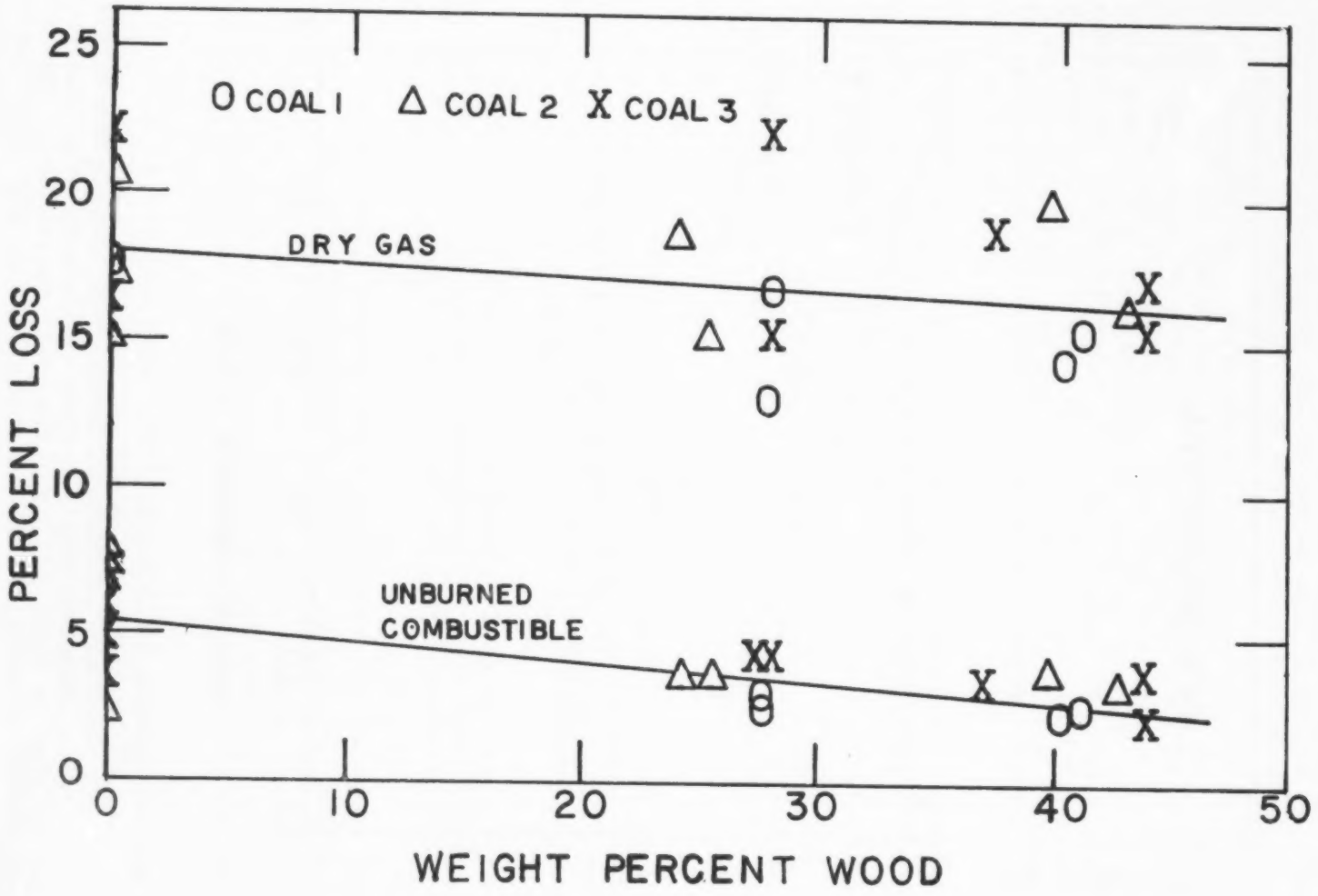


Figure 16. Dry Gas and Unburned Combustible Losses as a Function of Fuel Blend

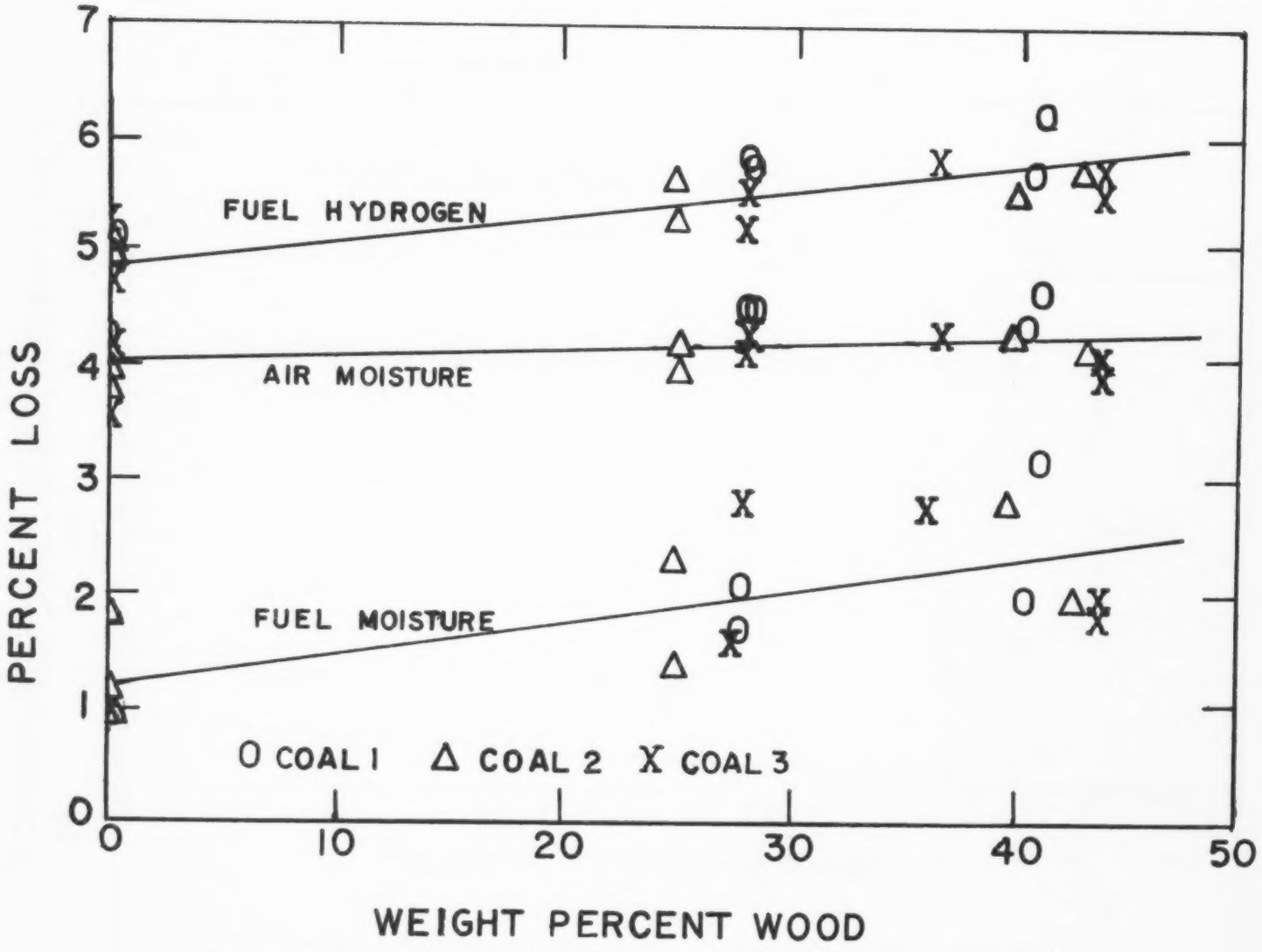


Figure 17. Moisture Losses Due to Fuel Hydrogen, Air Moisture, and Fuel Moisture as a Function of Fuel Blend

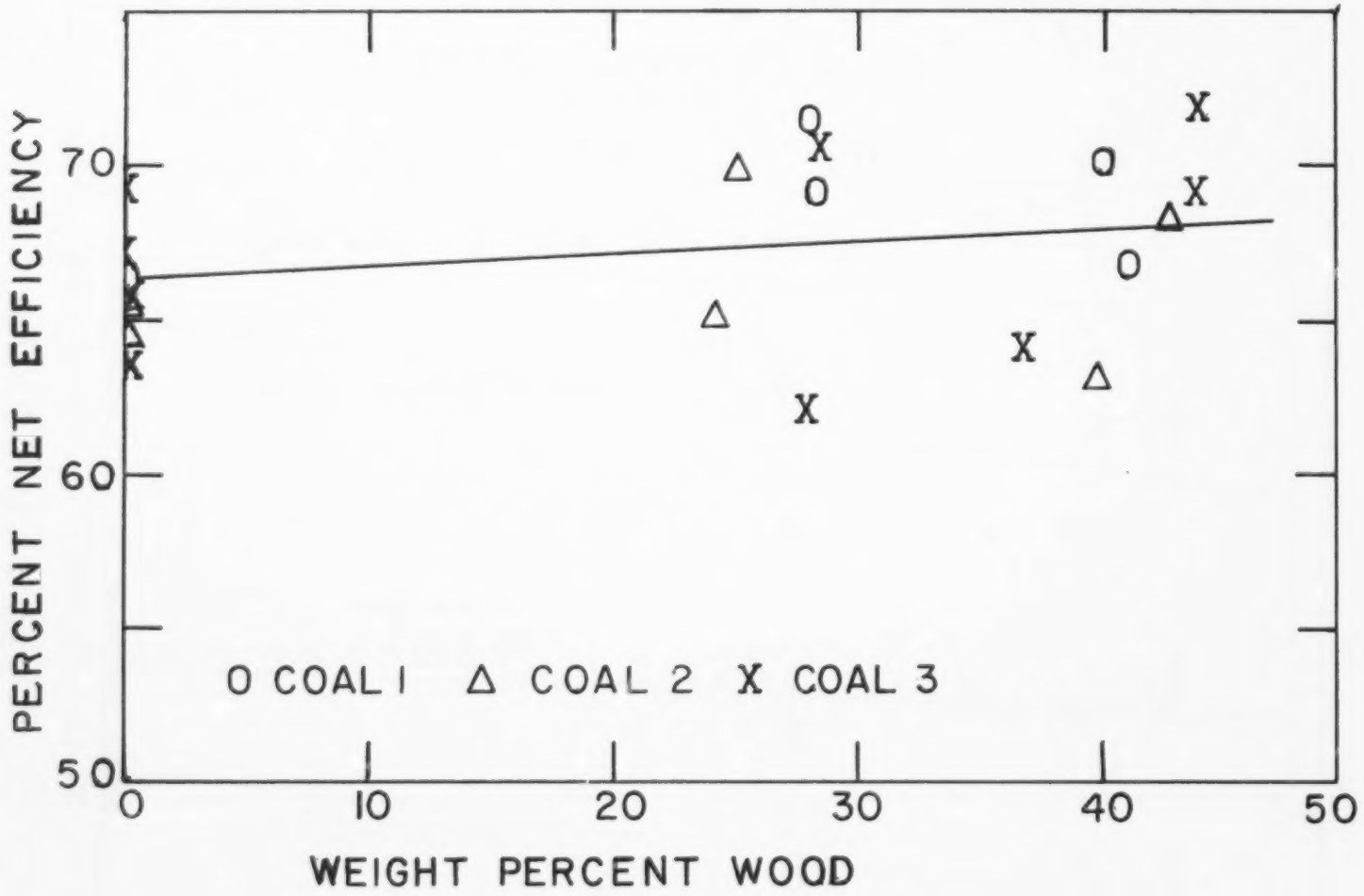


Figure 18. Net Efficiency Excluding Radiation and Unaccounted Losses as a Function of Fuel Blend

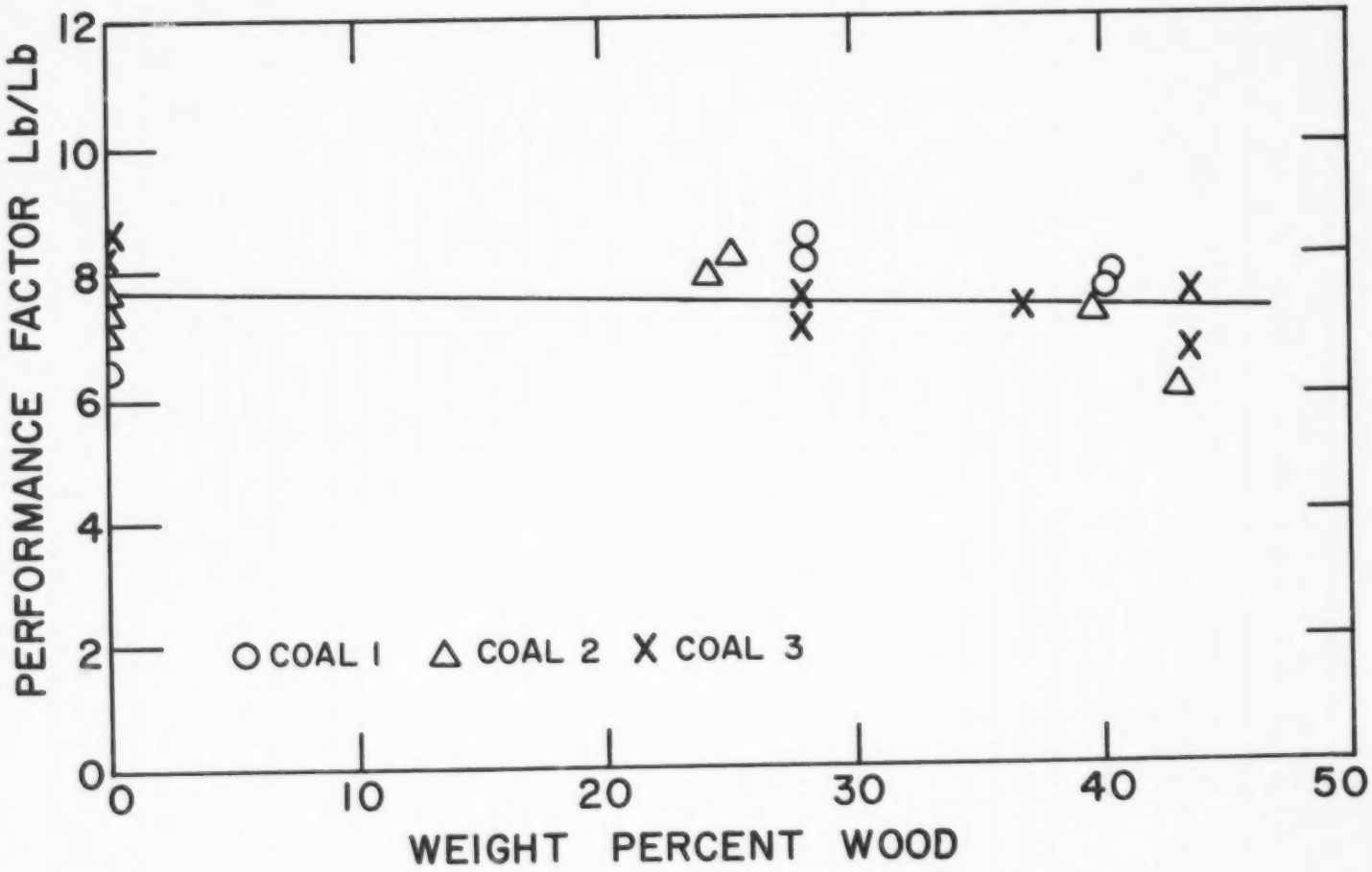


Figure 19. Performance Factor (Pound Steam per Pound Fuel) as a Function of Fuel Blend

As to the experience of actually burning the blended fuels, it was concluded that while the existing automatic control system worked relatively well for pure coal, some modifications would be necessary for the firing of a blended fuel containing more than 50% wood by volume. The firing of blended fuels containing, for instance, 67% wood by volume requires significant operator attention, especially when the moisture content is high and when load changes are severe. This is due mostly to increased restriction of the primary air flow caused by the faster stoker speed and the damp fuel. This problem would not be as severe with a spreader stoker.

In fact, during the summer test there was a period of one week where the area received nine inches of rain. This was in the middle of the testing and the wood stockpile was considerably depleted, making it much more susceptable to the moisture.

The fuel for the next week was mixed and loaded during the rainy spell, including mixing on the wet coal yard. The fuel was so wet, it dripped water and the wood was completely saturated. When this wet fuel was admitted to the boiler, the boiler began cooling rapidly. Holes appeared in the air pattern of the fuel bed and the only way the fire was maintained was with dry kindling thrown on top of the fuel bed. The result was a total loss of boiler load and the boiler was quickly switched back to coal. Several days were allowed for drying and then the fuel ran again. A similar situation occurred but by closing the damper and increasing the air until the boiler smoked (positive pressure) the fuel burned. Firing the wet fuel was a problem for several weeks following this occurrence. It wouldn't have been as severe if larger stockpiles of wood were maintained. The outer layer of wood tends to protect the center of the pile from absorption. The lack of ignition was quite a change from the earlier rapid ignition problems. During the entire testing program, close attention was given to any possibly slagging problems. There were none. Ash and fuel samples were taken daily and the decrease in ash was noticed as a function of increased wood content. The combustible in the ash was also noticed to be reduced with the addition of the wood.

There are a number of potential sources of error present in the experimental portion of this work, and the methods of calculation are especially sensitive to some. The largest single source of error probably resulted from the actual blending of the fuel, maintaining a uniform blend during fuel handling, and accounting for that blend in computation. The wood was often very moist and tended to cling to the sides of the fuel bunker, segregating the blend. Attempts to correct this were frequently made, but variations did occur.

An unresolvable source of error appears in the absorption of sulfur dioxide in the filter, stainless steel filter holder, and

stainless steel tubing. From information presented by Slowik and Sansone (16), and Byers and Davis (17), errors due to the stainless steel portions would be less than 1% while errors due to the filter paper itself could conceivably be as much as 10%, depending on the relative humidity of the flue gas.

A further look at the efficiency of this unit was made by calculating the cost of yearly operation. It was assumed that the unit (boiler No. 2) would be run for one year at an average load of 6000 lb/hr (2730 Kg/hr) of steam. This steam production is equivalent to the generation of 52,560,000 lb (23,914,800 Kg) of steam for the year. This boiler, referring to Figure 19, assuming all coal operation produced 7.7 lb of steam/lb of coal. To generate 52,560,000 lb of steam would require 6,826,000 lb of coal using the 7.7 lb/lb index. This was 3410 tons of coal. At $37.53/ton delivered the total coal cost was $128,000.

If the same boiler was run for the year at 6000 lb/hr with a blend of 1 wood to 1 coal, the steam required is still 52,560,000 lb of steam. The boiler production from Figure 19 was 7.5 lb of steam/lb of fuel. This production and load required 7,008,000 lb of fuel or 3504 tons of fuel. The cost to provide this fuel at $12.50/ton for the wood and $37.53/ton for coal was $106,950.00. This cost provided a savings of $21,050 over all coal operations and would have saved 887 tons of coal.

The amount of fuel for 2:1 was 3576 tons, which was 1645 wood and 1931 coal. The cost was $72,470.00 for coal and $20,560.5 for wood, a total of $93,032.5 or a potential savings of $35,000.60 and 1453 tons of coal. The dollar savings for this 6000 lb/hr load was plotted in Figure 20 for different wood weight ratios.

The completion of the testing was an attempt to use bark. A dump truck load of the bark was brought to tne power plant and blended with the coal on a 1:1 basis. There were immediate problems. The fuel segregated badly as it was elevated into the plant. The segregation was worse in the bunker and the boiler fuel was constantly varying from all coal to almost all fines to wood and coal. It was difficult to pass the combustion air through the blend and holes again appeared. An attempt was made to fire the boiler like it was fired with the wet fuel, but it just wasn't successful. The conclusion drawn is that the bark has to be hogged, but it would still contain excessively high concentrations of fines. The pelletizing of the bark was attempted and appears very promising, but wasn't tested. The HHV density and ash of the pellets were measured, and indicated they could possibly be fired alone with no coal. This possibility is very encouraging.

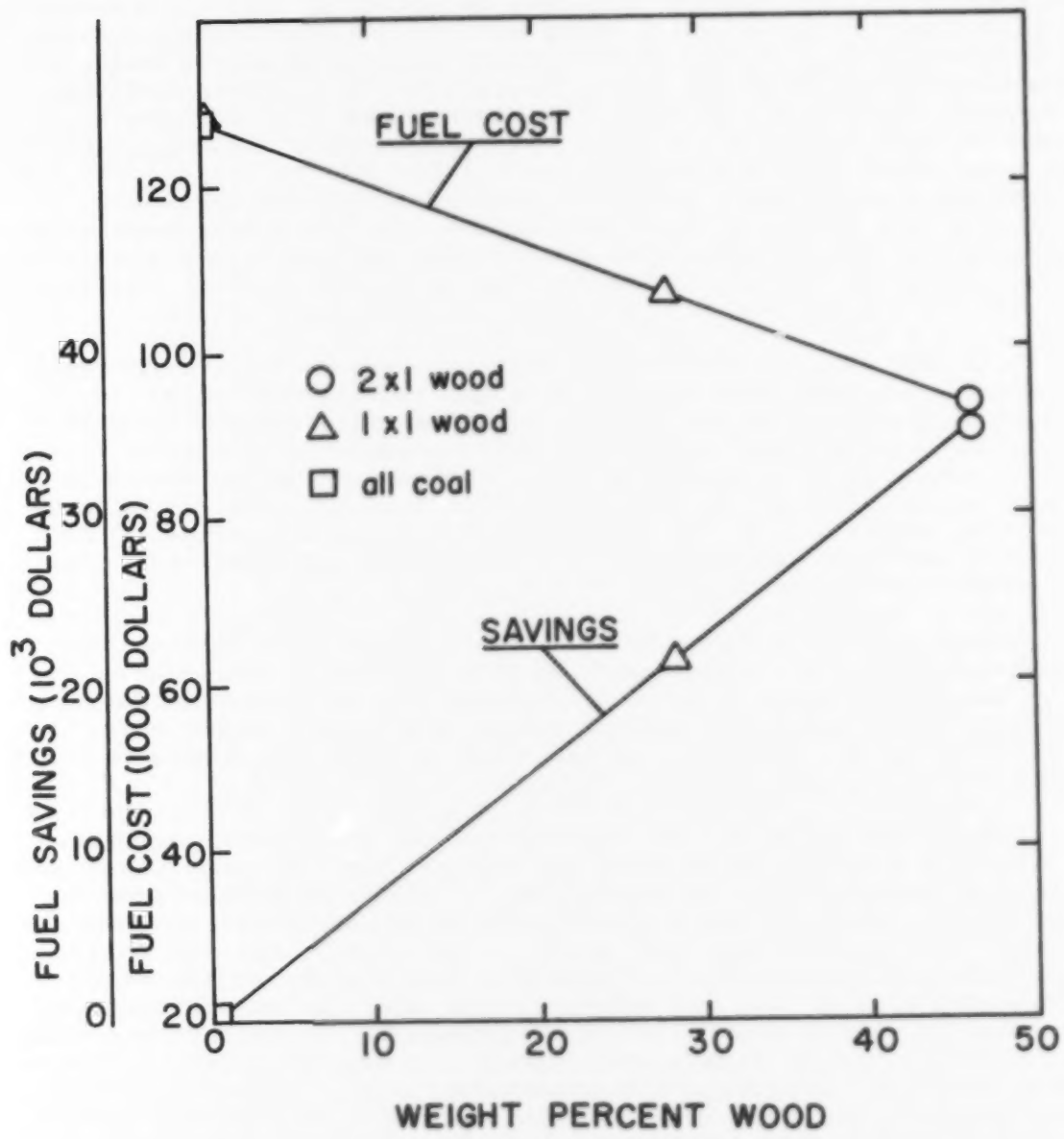


Figure 20. Economic Results from the Blended Fuel Use

REFERENCES

1. Lowe, R.A., "Energy Recovery from Waste", 2nd Interim Report, U.S. Environmental Protection Agency, (SE-360.ii), 1973.

2. Even, J.C., et. al., "Evaluation of the Ames Solid Waste Recovery System, Part I", Environmental Protection Agency Technical Series, EPA-60012-77-205, Nov. 1977.

3. Massengale, Robert, "Sawdust, Slab and Edging Weights from Mixed Oak Logs of the Missouri Ozarks", the National Logger and Timber Processor, April 1971.

4. Amos, J.A. and Massengale, R., "The Wood Residues of Missouri's Eastern Ozarks Region", Report to the Economic Development Administration, Oct. 1976.

5. "Timber Resource of Missouri Eastern Ozark Region", 1972, USDA, Forest Service Resource Bulletin, NC-19, Printed 1974.

6. Biotherm Energy Systems, Publication of American Wood Fiber Institute, Winn., Mich., 48896.

7. Hall, H.H., et. al., "Comparison of Fossil and Wood Fuels", Environmental Protection Agency Technology Series, EPA-60012-76-056, March 1976.

8. Jones, S.G. and Massengale, R., "Missouri Sawmill Improvement Program", a Publication of the Missouri Conservation Department, March 1975.

9. Massengale, R., "Missouri Forest Products Industries", Missouri Department of Conservation, 1975.

10. Environmental Assessment of Waste to Energy Processes, "Stationary Source Testing at Power Plant of University of Missouri at Rolla", EPA Contract No. 68-02-2166, MRI Project No. 4290-L, September 1977.

11. Badzioch, S., "Correction for an Isokinetic Sampling of Gas-Borne Dust Particles", Journal of the Institute of Fuel, March 1960.

12. Fryling, C.R., ed., Combustion Engineering, 2nd edition, Combustion Engr. Co., Riverside, Cambridge, Mass., 1966.

13. Smith, M.C. and Stinson, K.W., Fuels and Combustion, First Edition, McGraw-Hill, 1952.

14. Potter, P.J., Power Plant Theory and Design, 2nd Edition, Ronald Press Co., 1959.

15. Anonymous, Steam, 38th Edition, Babcock and Wilcox, New York, N.Y., 1972.

16. Slowik, A.A. and Sansone, E.B., "Diffusion Losses of Sulfur Dioxide in Sampling Manifolds", Journal of Applied Pollution Control Association, Vol. 24, No. 3, March 1974, pp. 245-247.

17. Byers, R.L. and Davis, J.W., "Sulfur Dioxide Absorption and Desorption on Various Filter Media", Journal of Applied Pollution Control Association, Vol. 20, No. 4, April 1970, pp. 236-238.

APPENDIX A

FACILITIES STATEMENT

The Power Plant to be used in the investigation has four boilers as listed below:

No. 1 Babcock and Wilcox, Integral Furnace and Boiler, 1944; 18,000 lb/hr at 150 psig saturated

No. 2 Babcock and Wilcox, Integral Furnace and Boiler; 18,00 lb/hr at 150 psig saturated

No. 3 Union Iron Works, 1957
35,000 lb/hr at 150 psig 405^{o}

No. 4 Erie City Iron Works
50,000 lb/hr at 150 psig, 405^{o}

All the boilers have Laclede chain-grate stokers. The power plant has two turbines as listed below:

Worthington Turbine, 150 psig steam with a General Electric Generator, 500 kw at 36000 RPM

Elliott Turbine Generator, 150 psig, steam 36000 RPM, 1000 kw.

The power plant's primary load is the heating and cooling of the facilities on the campus. The turbines are not presently being used.

APPENDIX B

DATA COLLECTED AND CALCULATED

TABLE B-1

DATA

Date	Blend by Volume	Firing Rate	% Sulfur Ash	% Carbon Ash	Weight Coal lb/lb	Sulfur in Coal
	Blend	#/hr	% SA	% CA	WF_c	S
6/14	1w:1c	886.7	0.72	21	0.72	2.44
6/15	1w:1c	758.5	0.5	21	0.72	2.44
6/16	coal	831.25	1.5	33	1	2.44
6/21	2w:1c	1026.2	1.43	22	.5967	2.44
6/22	c	954.3	0.53	18.3	1	3.12
6/22	2w:1c	902.1	1.72	20.7	0.5926	2.444
7/5	1w:1c	934.8	.27	20.2	0.7565	3.12
7/6	1w:1c	921.7	.98	20.6	.7473	3.12
7/7	2w:1c	947.0	1.08	21.6	.6027	3.12
7/8	coal	759.0	1.04	27.9	1	3.12
7/12	2w:1c	990.4	1.43	21	.5694	3.12
7/13	1w:1c	928	.05	21	0.72	
7/14	1w:1c	950	.058	19.8	0.72	1.911
7/19	2w:1c	1162	.055	22.6	.563	1.911
7/20	2w:1c	1048	.055	24.7	.563	1.911
7/21	3w:2c	956	.055	27.5	.6316	1.911
7/26	coal	884	.05	25.4	1	1.911
7/27	coal	835	.05	28	1	1.911
7/27	coal	885	1.3	30	1	3.12
7/28	coal	1019	1.2	31	1	3.12

TABLE B-2

DATA PLOTTED

Sulfur	Weight % Coal	SO_2 lb/10^6Btu	% Deviation	NO_x lb/10^6Btu
2.44	.72	3.985	126	.3843
2.44	.72	3.29	98.9	.306
2.44	100	2.84	75.7	.442
2.44	.5967	2.54	94.8	.405
2.44	.5926	3.06	107	.091
3.12	100	5.05	104	.05
3.12	.7576	4.94	115.7	.166
3.12	.7473	3.58	89.8	.54
3.12	.6027	4.51	124.9	.25
3.12	100	3.99	86	.24
3.12	.5694	3.18	101	.68
3.12	100	3.9	86	1.3
1.91	.563	1.49	72	.46
1.91	.563	2.07	99.6	.43
1.91	.6316	2.6	107	.51
1.91	100	3.03	100	.138
1.91	100	2.5	83	.36
3.29	100	4.54	.100	.37

TABLE B-2

DATA PLOTTED

Coal Sulfur	Opacity	Excess Air	Weight % Coal
1.91	9.4	95	72
1.91	7.3	77	56.3
1.91	7.8	104	56.3
1.91	8.2	112	100
1.91	8.1	116	56.94
1.91	8.2	147	63.16
3.12	7.4	113	100
3.12	7	123	100
3.12	6.7	108	1
3.12	6.6	106	74.13
3.12	7.6	153	60.27
3.29	7.1	129	100
2.44	6.4	88	59.26
2.44	4.5	58	72
2.44	4.6	76	59.67
2.44	4.25	106	72
2.44	6	122.5	100
2.44	6.5	135	100

APPENDIX C

REPORT OF ANALYSIS

MATERIAL:

One (1) sample of coal identified as Coal Sample 12-30-2

TEST REQUESTED:

Analysis of coal and screen test

RESULTS OF TESTS:

SIEVE SIZE	% RETAINED ON SIEVE	% PASSED SIEVE
1 in	19.81	80.19
.750 in	18.78	61.41
.500 in	22.00	38.41
.375 in	17.26	22.15
.250 in	12.18	9.97
# 4	3.54	6.43
# 6	3.17	3.26

	AS RECEIVED	DRY BASIS
% Moisture	7.60	-----
% Volatile Matter	35.83	38.78
% Fixed Carbon	47.00	50.86
% Ash	9.57	10.36
	100.00	100.00
% Sulfur	2.03	2.2
Btu	11,892	12,870
Btu (Moisture & Ash Free)		14,357

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/7-80-103		

4. TITLE AND SUBTITLE	5. REPORT DATE
Wood Waste as a Power Plant Fuel in The Ozarks	May 1980
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
V. J. Flanigan	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Mechanical Engineering Department University of Missouri - Rolla Rolla, Missouri 65401	EHE 624B
	11. CONTRACT/GRANT NO.
	R804270-010

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Industrial Environmental Research Laboratory Office of Research and Development U. S. Environmental Protection Agency Cincinnati, Ohio 45268	Final
	14. SPONSORING AGENCY CODE
	EPA/600/12

15. SUPPLEMENTARY NOTES

16. ABSTRACT

The report discusses the testing program conducted on a chain-grate stoker boiler with a blended coal and wood waste fuel. The boiler was designed to produce 18,000 lb/hr (8,200 kg/hr) of saturated steam at 150 psig (103.4 N/cm^2). The objective of the tests was to determine the difference, if any, in the performance and the emissions of the boiler co-firing wood and coal as compared to firing coal alone. Four different coals with different sulfur contents were fired with the wood waste. The wood waste content was varied up to 2/3 by volume.

Results indicate that particulate and nitrogen oxide emissions are not substantially altered by using wood waste as supplemental fuel with coal for the test conditions adopted in the program. Sulfur dioxide emissions decreased with increased proportions of wood waste in the coal-wood mixture, whereas total hydrocarbon concentration increased when wood waste content was increased. Cyanide concentrations were not substantially affected by substitution of wood waste for coal; particulate polycyclic organic emissions were below the detectable limits for all fuels used in the tests.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Wood Wastes Environmental Tests Boilers	Wood-Fired Boiler SASS Train SAM-1A Analysis Multimedia Effluent Sampling	

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to the Public	Unclassified	86
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

U.S. GOVERNMENT PRINTING OFFICE: 1980-657-146/5680

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Official Business
Penalty for Private Use $300

Please make all
detach or copy a
left-hand corner

If you do not wish
detach or copy t
upper left-hand c

EP

Postage and
Fees Paid
Environmental
Protection
Agency
EPA 335

Special Fourth-Class Rate
Book

necessary changes on the above label
nd return to the address in the upper

to receive these reports CHECK HERE □
his cover, and return to the address in the
corner

A-600/7-80-103